IMPACTS OF DISTRIBUTED GENERATION ON STABILITYOF ELECTRICAL POWER SYSTEMS

BY

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To my Beloved Parents, Wife, Son, Brothers and Sisters

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AI	Artificial Intelligence
AWEA	American Wind Energy Association
CHP	Combined Heat and Power
DG	Distributed Generation
DFIG	Doubly fed induction generators
FACTS	Flexible AC transmission system
FLC	Fuzzy logic controller
FSWTG	Fixed Speed Wind Turbine Generators
GA	Genetic Algorithm
IEEE	Institute of Electrical and Electronics Engineer
IG	Induction Generators
PCC	Point of Common Coupling
PI	Proportional – Integral Controller / Performance Index
PSS	Power System Stabilizer
PV	Photo-Voltaic
PWM	Pulse Width Modulated
SCIG	Squirrel cage induction generators
SG	Synchronous Generators
STATCOM	Static reactive compensator
VSC	Voltage source converter
VSWTG	Variable Speed Wind Turbines Generators
WECS	Wind Energy Conversion Systems
WF	Wind Farms
WT	Wind Turbines

NOMENCLATURE

d, q	Direct axis and quadrature axis quantities
r, s	Rotor and stator quantities
l, m	SG leakage and magnetizing inductance
f, k	SG Field and damper winding quantities
v_t	Machine's terminal voltage (pu)
v_d	d-component of the terminal voltage (pu)
v_q	q-component of the terminal voltage (pu)
K_A, T_A	Regulator gain and time constant
v_{ref}	Reference voltage value to control at (pu)
$v_{stabilizer}$	Input signal to the exciter (pu)
v_f	Exciter field voltage supplied to the synchronous machine
Tw	PSS washout block time constant (sec)
T1, T2, T3, T4	PSS Phase compensation blocks time constants (se)
P_w	Mechanical output power of wind turbine (W)
c_p	Performance coefficient of wind turbine
ρ	Air density (kg/m3)
A	Turbine swept area (m2)
v_{wind}	Wind speed (m/s)
λ	Tip speed ratio of the rotor blade tip speed to wind speed
β	Blade pitch angle (deg)
T_{servo}	Pitch Controller hydraulic servo time delay constant (sec)
w_r	Rotational speed of lumped-mass system (pu)
H_L	Lumped inertia constant of WECS shaft system (sec)
F_L	Damping coefficient of WECS lumped system (pu)

T_M	Mechanical Torque of wind turbine rotor (pu)
T_E	Electrical torque of the induction generator (pu)
R_{ST}	STATCOM's convertor's resistance (pu)
L_{ST}	STATCOM's convertor's inductance (pu)
C_{ST}	STATCOM capacitor (μF)
Q_{ST}	Instantaneous STATCOM reactive power (pu)
t	Time (sec)
$\Delta\omega$	Rotor speed deviation (pu)
Rs	IG Stator resistance (p.u.)
Rr	IG Rotor resistance (p.u.)
Xs	IG Stator leakage inductance (p.u.)
Xr	IG Rotor leakage inductance (p.u.)
Xm	IG Mutual inductance (p.u.)
Hg	IG Per unit inertia constant of generator (sec)
X	Transformation reactance, (p.u.)
Xl	Transmission line reactance (p.u.)
T'do, T"do	SG Transient and Sub-Transient d-axis time constants (sec)
T'qo, T"qo	SG Transient and Sub-Transient q-axis time constants (sec)
H	SG Inertia (sec)
D	SG Damping Factor
Xd, X'd, X"d	SG direct-axis reactance (p.u.)
Xq, X'q, X"q	SG quadrature-axis reactance (p.u.)

THESIS ABSTRACT

Name: **Abdullah Mohammad Al-Ben Saad**

Thesis Title: **Impacts of Distributed Generation on the Stability of Electrical Power Systems**

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Environmental concerns, market forces, and emergence of new technologies have recently resulted in restructuring electric utility from vertically integrated networks to competitive deregulated entities. Distributed generation (DG) is playing a major role in such deregulated markets. When they are installed in small amounts, their impacts on the system may be negligible. When their penetration levels increase, however, they may start affecting system performance from more than one aspect. System transient stability needs to be re-assessed after the emergence of DG.

This thesis attempts to address the impact of DG on system stability under different operation conditions. Wind Energy Conversion Systems (WECS) are involved as a DG technology. Dynamic models for different system components such as synchronous and induction generators, and Wind Turbines are presented first. Then, the impacts of WECS on the stability of an electrical power system are addressed taking into account different ratings and installation locations. After that, an attempt to enhance system stability is performed using optimized STATCOM control schemes and Power System Stabilizers (PSS) whose parameters are tuned up using Genetic Algorithm (GA) for optimum control. Time-domain simulations are carried out under different WECS penetration levels and installation location within the grid. Simulation results show that STATCOM has contributed to an enhancement in the transient stability of induction generators. Moreover, they show the effectiveness of the optimized PSS in damping out synchronous generators' rotor angle oscillations.

Key Words,

Distributed generation, deregulation, stability, wind turbines, induction generators, STATCOM, power system stabilizers, genetic algorithm, multi-machine system.

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ملخص الرسالة

اسم الطالب : **عبدالله بن محمد حسن البن سعد**

عنوان الرسالة **:دراسة تأثير وحدات الطاقة الموزعة على استقرارية الشبكات الكهربائية**

التخصص : **هندسة كهربائية**

تاريخ التخرج : **يونيو 2009 م**

نظراً للظروف البيئية والضغوط الاقتصادية ودخول كثير من التقنيات الحديثة في مجال توليد الطاقة الكهربائية مما أدى الى إعادة هيكلة خدمات الطاقة من الشبكات الرأسية إلى وحدات صغيرة تنافسية. توليد الطاقة الموزع يلعب دورا رئيسيا في مثل هذة البيئة. إن تأثير وحدات توليد الطاقة الموزعة قد يكون ضئيلا عندما تُدرج في الشبكات الكهربائية بنسب صغيرة, إلا أن تأثيرها على استقرارية الشبكة يتفاقم مع دخولها الشبكة بنسب عالية. وبالتالي فإن استقرارية الشبكات الكهربائية بحاجة إلى إعادة تقييم ودراسة مع وجود وحدات الطاقة الموزعة.

هذه الرسالة بصدد دراسة مدى تأثير وحدات الطاقة الموزعة على استقرارية الشبكات الكهربائية وقد تبني وحدات الطاقة المعتمدة على الرياح كمثال للطاقة الموزعة. هذه الرسالة تحتوي على نماذج ديناميكة لمحاكاة أجزاء الشبكة الكهربائية كمولدات الطاقة التقليدية, والمحفزات الكهربائية, وأنظمة الطاقة المعتمدة على الرياح. وستستخدم هذه النماذج في تحليل استقرارية الشبكة الكهربائية مع وجود أنظمة الطاقة المعتمدة على الرياح بنسب وأماكن توليد متفاوتة. بعد ذلك هذه الرسالة تطرح أساليب لتحسين مستوى استقرارية الشبكة وذلك باستخدام تقنية "المعوضات الساكنة والمتزامنة " و تقنية "نظم مهدئات الطاقة" والتي سيتم تصميم نظم التحكم فيها باستخدام تقنية الهندسة الوراثية.

الكلمات المفتاحية:

وحدات الطاقة الموزعة, إعادة هيكلة خدمات الطاقة, استقرارية الشبكات الكهربائية, وحدات الطاقة المعتمدة على الرياح, الهندسة الوراثية, المعوضات الساكنة والمتزامنة, نظم مهدئات الطاقة.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران, المملكة العربية السعودية

يونيو 2009 م

CHAPTER 1

INTRODUCTION

1.1 Overview

Environmental concerns, market forces, and emergence of new technologies have recently resulted in restructuring electric utility from vertically integrated networks to competitive deregulated entities. In a typical deregulated environment, the electrical utility will not be thought of central generation units located at remote places, delivering power to end users' loads via long and high voltage transmission lines in a unidirectional power flow. Rather, it will become an open market offering competition in the generation, transmission, distribution and delivering of electrical energy. It may include various technological power generation facilities that could be sited near or at load centers. These generation facilities are termed Distributed Generators.

1.2 Definitions

Distributed Generation (DG) is defined in many ways. These are based on generation capacity, unit rating, and based on voltage levels to which it is connected, the technologies it is utilizing, and technical and non-technical values it is adding to the system. The following diagram depicts these bases.

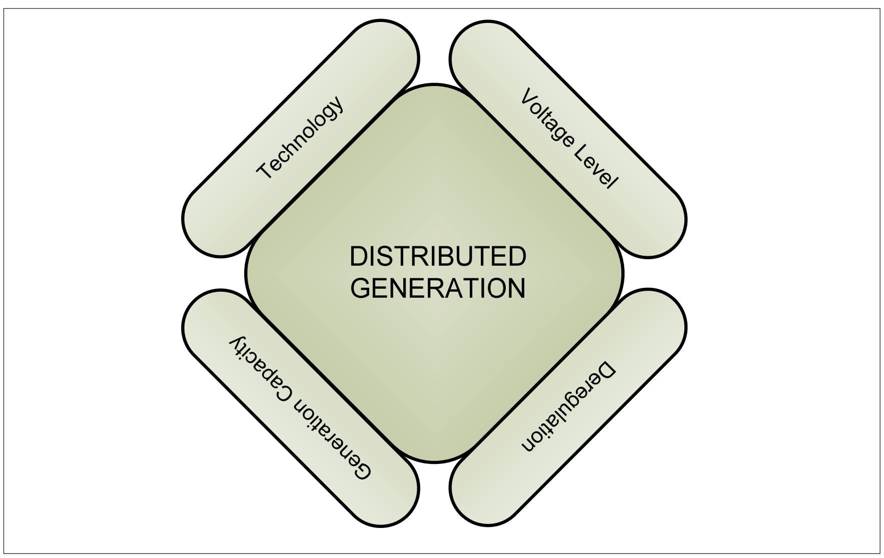

Figure 1.1: Explanatory Diagram Shows Interpretations of DG from Different Aspects

When based on its generation capacity, DG cannot be clearly and consistently defined as there is no certain maximum generation capacity based on which DG could be defined world wide. For example, DG in Sweden is any generation unit up to 1,500 kW while in England the term DG is used for power units with less than 100 MW capacities. Regulations, currently operating in the Australian States of Victoria and New South Wales, DG is often defined as power generation with capacity of less than 30 MW. [1-5]

Most authors, if not all, agree on that DG's are connected near load centers at distribution voltage levels. However, the distribution voltages are not well defined and vary among different utilities. In many cases, there is no separation between voltage levels of distribution and transmission systems. Therefore the definition of DG based on the voltage levels to which it is connected is not considered an appropriate criterion [1-5].

The definition of DG is sometimes thought of only those generation units utilizing renewable resources such as wind, ocean waves, solar, and so on excluding those running on fossil fuel gas, nuclear reaction or coal [5]. A DG is also defined based on the tendency toward a competitive environment and changing the way generation companies are doing business. Generation, transmission and distribution of electrical energy that was once operated by a single player in the market is now being changed. Independent companies are now entering the market running the generation utilities, transmission lines, or distribution networks. They are called Gencos, Transcos and Discos, respectively.

In summary, the term DG is a wide umbrella covering many unlike definitions. Generally, DG is defined as one or more of the following: [1-5]

- Facilities located at or near a load center.
- Relatively, small-scale generation units from few kilowatts to few megawatts.
- Generation units based on renewable resources.
- Facilities providing enhanced value other than energy and capacity.
- Residential or commercial back-up generators.

1.3 Advantages

Having understood the principles of DG and how it is perceived from different angles, one may analyze the potential impacts that DG has on the grid. Provided that they are carefully selected and investigated, DG units' type of technology, size, location, and operation mode could result in invaluable benefits in system operation. In many cases, it has been concluded that DG can improve system voltage profile with unit's generation capacity and location playing a vital role in this improvement [6-8]. Moreover, the operation modes of the DG units within the network are also important in such improvement.

Another important benefit DG is offering is the reduction in line losses. This is due to the fact that DG participates in relieving transmission lines by delivering active power to loads directly through distribution network [2]. Nevertheless, this is not always true since reverse power flows from larger generation units can raise line losses [8].

In practice, conventional power plants emit many pollutants such as Co_x, NO_x and SO_2, which are directly proportional to the total active power generated. These emissions are contributing in the global warming and world-wide climate change or what is usually known as "Greenhouse Effect". DG units connected into grid will minimize the dependence on power outputs from conventional generation units and hence reducing emissions. Besides, DG units utilizing *Renewable Resources* will further contribute in emissions reduction [1-2]. DG has, in contrast, some negative impacts on the environment as well when some technologies, wind turbines and photo-voltaic for instance, need larger area for construction than the conventional plants [8].

The impact that DG has on power system stability is of a major concern where many investigations are being carried out. It is truly attracting attention of scientists and researchers all over the world. Benefits and drawbacks of DG on power system stability will be detailed in a separate section of this thesis.

1.4 Distributed Generation Technologies

The objectives of this section are to give a quick background on some of existing DG technologies available in the industry and shows comparisons in terms of generation capacities, installation and operation costs of each. The technologies will be discussed separately in individual sub-sections.

1.4.1 Solar Cells or Photo-Voltaic:

Solar cells or Photo-Voltaic (PV), invented in 1950s, produce electricity from sun light by converting the light beams of the sun into flow of electrons and producing current [9]. Although the current produced is not very high and one needs to install many of these cells together in order to produce enough power, solar cells are very reliable, have no moving parts, and emission free [9]. Yet, they are very expensive in both capital and installation costs. The power generation costs per kilowatt of PV, for example, could be up to ten times the generation costs by other technologies as could be seen from table 1.1.

Table 1.1: Guideline electricity generation costs today (cents/kWh) (Source: Solarbuzz)

Combined cycle gas turbine	3-5
Wind	4-7
Biomass gasification	7-9
Remote diesel generation	20-40
Solar PV central station	20-30
Solar PV distributed	20-50

1.4.2 Wind Energy Conversion Systems:

Wind Energy Conversion Systems (WECS) generate electrical power by converting the kinetic energy from the wind into a mechanical energy driving a generator. WECS, which are normally consisting of two or three blades wind turbines arranged either vertically or horizontally, are sited at the top of *Wind Towers*. They are constructed and controlled in a way so that maximum power could be extracted from wind taking into account height of the tower, blades radius, aerodynamic characteristics of the blades, and at last the site and topology arrangement of wind turbines inside a *Wind Farm*. Wind Farms, sometimes referred to as *Wind Park*, is a term given for a set of wind turbines grouped together in a specific manner to enlarge size of power generation.

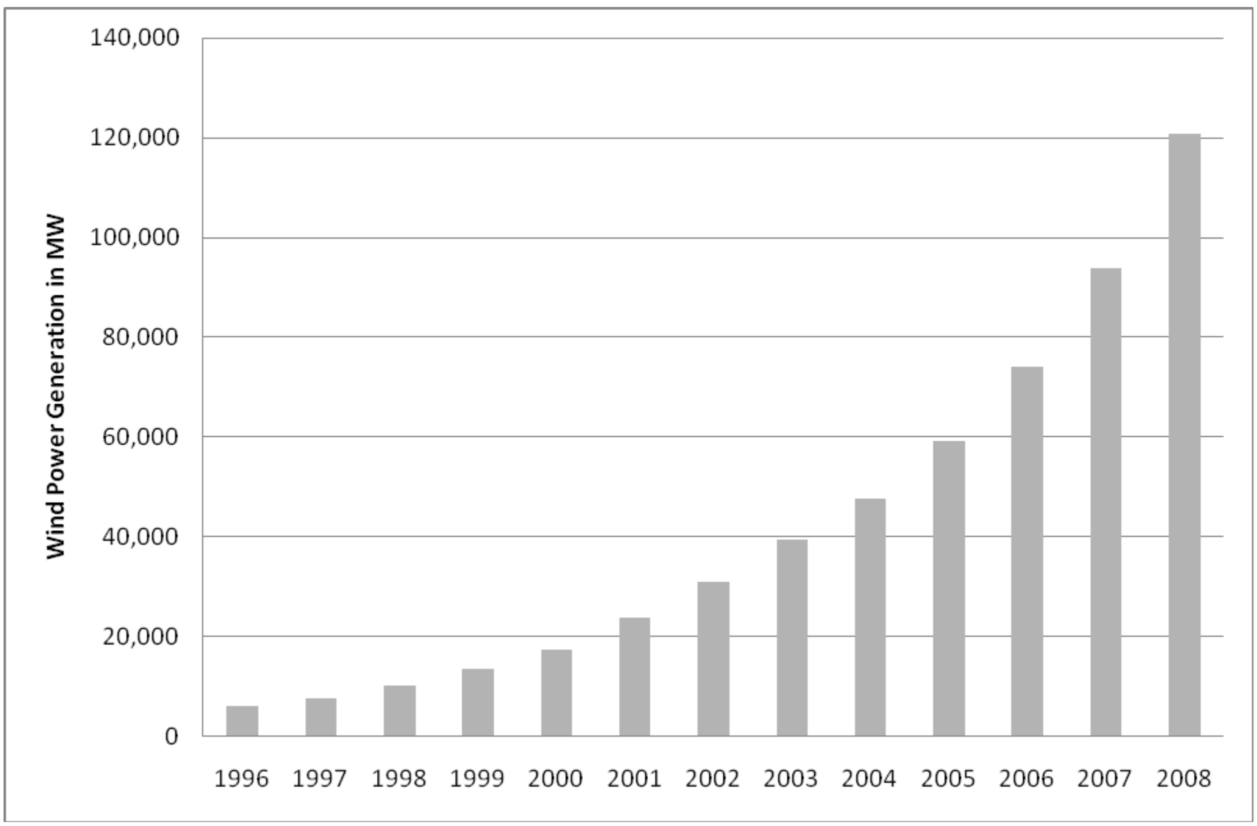

Figure 1.2: World-Wide Development in Installed Power Capacity (Regenerated from AWEA/EWEA)

Since the last two decades and power generated from wind is maintaining a rapid increase. According to the American Wind Energy Association (AWEA), an amount of over than 120,000 MW generation capacities was installed by end of 2008. Figure 1.2 demonstrates the growth in wind power generation capacities in USA, Europe and the rest of the world. [10]

This increment is a result of the developments in Wind Turbine Generation unit size in term of wind tower height and blades diameter which magnify power extraction [11]. Figure 1.3 shows how wind turbines size has been developed since the last twenty years.

Secondly, the size of installation projects deploying wind turbines as a generation technology is also increasing [11]. Instead of having individual wind turbines, wind farms with multi tens or even hundreds of wind turbines are erected all over the world delivering power at a wide range of its running capacity.

1.4.3 Combined Heat and Power Technology (CHP):

In CHP, the by-product heat that is radiated into atmosphere and wasted in conventional power plants is positively utilized. Additional to being a fuel-efficient energy technology converting around 90% of fuel into energy, CHP offers variety of extra benefits. One of the benefits CHP is offering is the reduction in carbon emissions. It is found that if manufacturers in 1994 had generated steam and electric needs with the existing CHP technology, they would have reduced carbon emissions by around 20% [12]. The wide range sizes of CHP, from few kilowatts to multi-tens of megawatts, is considered another benefit that provides various applications of such technology from small installations at homes up to large industrial plants projects [13].

Currently, there are four CHP plants in Saudi Arabia with production capacity of 1,083 MW. The plants provide power and steam to Saudi Aramco facilities. Further cogeneration projects within the company will see the light very soon.

Besides PV, CHP and WESC, other possible DG technologies include Internal Combustion Engines, Microturbines, Fuel Cells, Hydro-Power Generators, and Geothermal Energy. Details about these technologies could be found in [1-11, 15-17]. The following table highlights major characteristics of some of DG technologies.

Table 1.2: Summary of Present Costs and Uses of Distributed Generation Technologies

Characteristics	Internal Combustion Engine	Wind Turbine	Microturbines	Fuel Cell	Photo-Voltaic
Size Range (kW)	50-5000	50-2000	25-75	2000-5	1-100
Current Installed Cost ($/kWh)	200-500	1000 -1500	1000 -1500	3000-4000	1500-6500
Electricity Cost (/kWh)	5.5-10	5.5-15	7.5-10	15-20	15-20
Applications	Back-up Power, Peak Reduction	Green Power, Remote Locations	Back-up Power, Peak Reduction	Power Quality, Base Load	Stock Watering, Grid Independence

1.5 Distributed Generation and Power Systems Stability Problem

The analysis of power systems transient stability is a complex problem demanding detailed models for system's generators, exciters, governors, stabilizers and loads. There are so many dynamic models in the literature that would require books to highlight their characteristics. Dynamic models representation in dynamic simulation for different equipment in the system could be found in [13-18]. Equipment models are formed as non-linear differential equations that are solved by different methods and techniques. [13-14]

There are many factors that affect stability of electrical power systems. Some of them include:

- Loading of generation units.
- Type, location and duration of system disturbances.
- Inertia of generation units.

Studying stability of power systems are well covered in the literature. With the emergence of DG in the grid with relatively so high capacities that could impact the operation of the system, stability studies kept growing. When installed in small amounts, on the other hand, DG impact on system stability may be neglected. [15-17]

Since there are various DG technologies currently connected to the grid, system dynamic behavior will be unlike system dynamics with conventional generating units. Therefore, dynamics are being analyzed with each single technology adopted by DG and that of course requires developing dynamic models for each DG technology.

As stated earlier, DG is continuously supplying power to the grid at different levels ranging from few kilowatts to multi megawatts. Active power generation by conventional generation units and line flows are now changed leading to a change in the operations of the network. This in turn has influenced system stability.

DG units, as the name indicates, are scattered in many parts of the network. Even though, in many cases the total power generated and consumed in a given network remains unchanged, the line flows due to installation of a DG unit at specific location will alter line flows and hence the stability profile of the network. This is considered another factor affecting the problem of stability.

1.6 Thesis Motivations

The work in the field of distributed generation has been growing since their emergence in electrical power systems in large scales. DG technologies and penetration levels is motivating researchers to analyze their impacts on the stability of electrical power systems. It is attracting researchers to develop and validate new techniques to minimize their impact on the stability. This thesis attempts to address the impact of DG on system stability under different operation conditions.

Beside their environmental and low operation costs advantages, Wind Energy Conversion Systems (WECS) rapid development over the last decades have resulted in wide acceptance of this technology as a good candidate for use in DG applications. Many researches are carried on to emphasize their stability performance. This thesis will therefore select WECS as DG technology to be studied and investigated in relation to system stability.

1.7 Thesis Objectives

This thesis will be dedicated to study the impact of WECS on the stability of multi-machine electrical power systems. So, dynamic models will be developed for system's machines, WECS, and other auxiliary systems such as exciters and regulators. The stability of multi-machine electrical power system will be studied under different scenarios that will examine not only the impact of WECS's location within the grid, but also it will investigate how WECS penetration levels will contribute to the impact on stability.

The thesis will propose some control techniques that are designed to enhance stability of the system. An optimization algorithm will be introduced for the design purposes of the proposed controllers. The algorithm is repeated for each scenario examined. Comparison will be made to differentiate between each control technique's benefits to the system.

1.8 Thesis Organization

This thesis is organized as follows. First, a literature survey is presenting previous work related to DG advantages, disadvantages, modeling, and impacts on stability.

Then, mathematical modeling of WECS, including fixed-speed wind turbines, induction generators, pitch angle controllers, and shaft system, to be used in dynamic simulations is presented. It also includes mathematical models for major system components like synchronous generators, excitation system, and control schemes. A solution algorithm is also demonstrated.

After that, time-domain simulations for a study case are presented in chapter 4. Proposed designs for controllers are discussed in chapter 5 followed by simulation results. Chapter 6 reviews major achievements and concludes the thesis.

CHAPTER 2

LITERATURE SURVEY

2.1 Overview:

The problem of power system stability due to emergence of DG is becoming complex as more DG technologies are connected to the grid with high penetration levels. This problem is influenced by more than one factor. The stability of electrical power systems is influenced by the type of technology, dynamic modeling of DG technologies and their control schemes, types of disturbances, penetration levels, and location of DG units within the grid.

To make this problem simpler and easy to understand, each factor will be discussed apart. This chapter will give an overview of the work done on the impact of DG on the stability of electrical power systems. It is organized as follows. First, technologies of DG and their impacts on stability, environmental and economical aspects are addressed. Then, since WECS are selected as DG technology to be emphasized on, the second section will illustrate their concepts and types. It will also present modeling techniques and control schemes in the literature. Finally, a review of system stability problems due to WECS will conclude this chapter.

2.2 Distributed Generation (DG) Technologies:

DG technologies vary from simple to complex, common to rare, and small in size to big generation units. DG technologies influences have been studied in the literature from more than one aspect. Stability, power quality, economy and environment influences have been analyzed. The following subsections will approach each influence apart.

2.3 Impacts of DG:

2.3.1 Influences of DG Technologies on the Stability

The penetration of DG into electrical power systems has raised many challenges in terms of stability, and hence analyzing the impact of DG technologies on the stability of electrical power systems is one of the ongoing topics under study for the last couple of years. Analysis for DG technologies and stability problems were performed.

In [15], microturbines and fuel cells are simulated as DG technologies to study their impact on the angle, voltage and frequency stability of a hypothetical electrical power system. The author found that the stability of an electrical power system can be improved if suitable type and appropriate locations are selected for the DG.

In [16] Reza simulated synchronous and asynchronous machines, with and without grid voltage and frequency controls. It is concluded that DG plays a vital role in limiting the amount of power flows over the transmission lines and hence improving their transient stability.

Research work by Slootweg in [17] using the same DG technologies but with different penetration levels showed that the type of technology is also contributing to the upgrade/degrade of power system stability.

Frequency stability problem is studied in [18] for a distribution network with the presence of steam turbine generators, combustion turbine generators, hydro turbine generators, and wind turbine induction generators. This research demonstrated the dynamic models for each DG technology.

2.3.2 Influences of DG on Power Quality

Another field of studies where technologies of DG are focused on is power quality studies. In [19], two types of DG technologies are studied for harmonic analysis and voltage sags, namely, synchronous and induction generators. The author concluded from a number of operation scenarios that higher ratings of synchronous generators are required to achieve satisfactory power quality for the system.

2.3.3 Influences of DG on the environment

The number of studies and researches done on the environmental aspects of DG technologies is very large in order to prove its feasibility of minimizing emission of CO_2 and oil dependence. This, of course, is considered as one of the most important features offered by DG.

Forces to generate electricity from renewable and environmentally friendly technologies are considered as one reason toward adapting various DG technologies all over the world. Researchers, therefore, had to measure and compare these technologies' benefits both in quality and quantity points of view. For example, Qian introduced in [20] environmental benefits indices for wind turbines, photovoltaic, fuel cells and microturbines in China. Qian calculated the emission intensity of pollutants such as SO2, NO2, CO and CO2 due to generation of one kWh of electricity.

2.4 WECS Modeling and Control Schemes

Among various DG technologies, wind energy conversion systems (WECS) have attracted attentions of scientists and researchers due to a number of reasons. First of all, WECS is emission free type of DG that supports the need for a green power source. It is derived from natural sources that are relatively available and abundant throughout the day, which is unlike the availability of solar energy, for example. Finally and most importantly, continuous developments in WECS technologies have led to better efficiency, reliability, and economical feasibility of this technology.

Researchers have spared no efforts in studying all types of WECS, developed dynamic models for transient analysis, and compared influences of this type of technology with others. This part of the chapter demonstrates types of WECS and the dynamic modeling of each type for transient stability analysis.

WECS are basically composed of wind blades, designed and used to efficiently convert kinetic energy from wind to mechanical energy. This mechanical energy is utilized in driving wind turbines which in turn drive electrical generators. There are various types of wind turbines in use in the field.

Wind turbines classes and features are discussed in the literature [22-28]. Wind turbines are basically classified into three main classes. They are the constant speed wind turbines with squirrel cage induction generators (SCIG), variable speed wind turbines coupled with doubly fed induction generators (DFIG), and variable speed wind turbines with direct drive synchronous generators (SG). Dynamic models and modeling issues associated with each type of those will be discussed in the following sections.

2.4.1 Fixed Speed Wind Turbine Generators (FSWTG)

A reduced-order fixed speed wind turbine generator model is presented by Trudnowski [22]. It is derived from a highly detailed mechanical and aerodynamic turbine model and by using model reduction technique all dynamic effects outside the electromechanical range are removed. The induction generator is modeled using standard two-axis induction machine model. The models are simulated and proved for accuracy in more than one test system.

Electrical and mechanical components of FSWT driving SCIG are presented in [23]. The mechanical aerodynamic part of FSWT that relates wind speed with the mechanical torque is modeled by using performance coefficient curves. The induction generator is modeled using a fifth order model. The shaft system is modeled in two different ways. The first approach of modeling is the lumped mass shaft model which neglects the electromechanical interactions between FSWT and the grid. In contrast, the second approach segregates the rotor damping coefficients and inertia constants of the turbine and generator. In this case, the electromechanical interactions between FSWT and the grid are taken into consideration. This way of modeling is known as two-mass shaft model. Also modeled is the blade angle control scheme which is used to control the output power of the wind turbine. It is also used for stabilization of wind turbine at faults by reducing the mechanical power and achieving better re-establishment of the terminal voltage. There are two proposed models for the blade angle control. They are simulated and compared by a single machine infinite bus system. Results show that the differences between the two control models are quite similar in case of lumped-mass shaft model. They are very different, however, when the two-mass shaft system is modeled. This illustrates the impact of shaft modeling on stability analysis.

Different shaft systems for wind turbines are presented in the literature. They are lumped-mass, two-mass, three-mass and six-mass shaft models. In [24], the author has presented those models and compared their performance in transient stabilities. He discussed six-mass shaft system from which he derived three-mass and two-mass shaft systems. Simulations are carried out on two different systems with different types of disturbances. It is concluded that two-mass shaft system is sufficient for the transient stability analysis of WECS.

Another research work where one, two, and three-mass shaft systems are modeled and compared is in [25]. The three-mass wind turbine equivalent model considers both the bending flexibility of the blades and the torsional flexibility of the drive-drain shaft between the wind turbine and induction generator. The results have shown the three-mass equivalent model including both the blades and shaft flexibilities may be more appropriate to accurately analyze the transient stability.

FSWTG with active stall control is modeled and evaluated in [26]. Active stall control manipulates the pitch angle in the negative direction, from -90˚ to 0. Changing the pitch angle will contribute in controlling the active power generated and therefore enhancing the stability. It is found that the stability margins of FSWTG are higher with active stall control at lower active power operating points.

2.4.2 Variable Speed Wind Turbines Generators (VSWTG)

Dynamic models for wind turbines driving Double Fed Induction Generators (DFIG) are important to investigate the impact of the widely existing variable-speed wind technologies. Along with their control systems, many dynamic models ready to be incorporated in simulation packages are developed.

A general model representing variable-speed wind turbines consists of several subsystems as per [29]. Subsystems are modeled for wind speed to generate wind speed signals, rotor model simulating conversion process of kinetic energy from the wind to mechanical power fed to the generator, and generator model. Also included in the general model are rotor speed controller model, pitch angle control model that controls rotor speed, voltage control model maintaining terminal voltage near the specified set point, and protection system model. Further details of each component of this general model could be seed from the source.

In [33], dynamic models are presented for variable speed wind turbine with DFIG, and back to back voltage source converter, speed, pitch angle and voltage controls. The models are developed assuming that all rotating masses are represented by one mass, or lumped mass, that will reduce the complexity of the models.

The induction machines, for both FSIG and DFIG, modeled in [34] are of fourth order and simplified to a second order where the DC components in stator transient currents are neglected. In addition, DFIG converters control, speed control, electromagnetic torque control, power factor and terminal voltage controls are modeled. The models are simulated in a two-bus double circuit system. Results show that the speed and power factor control modeled within the DFIG system assists in improving stability. Simulation results of the DFIG model voltage control technique illustrate the improvements in network voltage profiles.

It has been observed that GE has ongoing efforts to develop new models for WECS. An example can be found in [35] where wind turbine generator model is described. In addition, a simplified electrical controller and wind turbine models can be found. Same aerodynamic model used in the previous work is used in here. The model is tested by substituting a synchronous generator in a multi-machine system with wind turbine generators.

2.4.3 Wind Farm Modeling (WF)

In order to simplify the calculations and minimize efforts required to model each wind turbine in a wind farm, an aggregated modeling of wind turbines might be necessary. Aggregated wind farm models for both constant speed and variable speed wind turbines can be found in [39]. Aggregation for constant speed wind turbines is based on the assumption that the total MVA rating of wind turbines, mechanical power and compensating capacitors equal to the sum of individual wind turbines.

On the other hand, aggregated model for variable speed wind turbines is based on totalizing the electrical power generated by each wind turbine instead of mechanical power as in fixed sped wind turbines. Simulation results out of the aggregated and detailed models show that there is a big degree of performance similarities of both models. However, aggregated models less simulation time than distributed model.

Aggregated WF model [40] is based on the assumption that each wind turbine within the wind farm will be subject to the same disturbance torque and will oscillate in phase with each other. Therefore, wind turbines can be mechanically combined together and the equivalent wind farm model sums up the inertia, spring and damping coefficients of the individual turbines. The equivalent induction generator model is obtained using weighted admittance averaging method where the equivalent machine parameters (R1, R2, X1 and X2) are calculated from the average admittances of each branch of the induction machine equivalent circuit.

2.5 WECS and the Stability Problem

As the penetration levels of WECS become larger from year to year, it is necessary to consider the potential impact that those systems might have on the stability of electrical power systems. A number of researches are being undertaken to investigate the impact, and provide solutions to overcome the challenges due to WECS. Stability problems analyzed in the presence of WECS are summarized in the following sections.

2.5.1 FSWTG and VSWTG influences on the Stability

A good number of comparisons between FSWTG and VSWTG are made to conclude the impact each type of WECS has on the stability of electrical power systems [42-43]. In [42], for instance, dynamic simulations are carried out on a real electrical power system where the two types of WECS are installed at a time. Following a disturbance, a drop at the terminal voltage of FSWTG is observed which is not the case when VSWTG is installed instead. This is justified by the fact that VSWTG driving DFIG do supply the grid with reactive power that can maintain the terminal voltage at its nominal value.

The two technologies are deployed in the Spanish System, which will have 13,000 MW produced from WECS by 2011. It shows that variable speed devices to be better than fixed speed devices in term of stability. It is also noted in this research that power generations fluctuations from WECS are negligible compared to the effects of short circuits in the power grid. The simulation has assumed that the power input from WECS is kept constant throughout simulation periods. [43]

WECS are tested for modal analysis where high penetration levels are emerged in a two area system. This system is simulated for four operation scenarios. In each scenario, WECS substitutes a portion of active power generated by synchronous generators. The results of this investigation show that the inter-area mode tends to become more stable as the real power of the WECS approaches its nominal value. They tend to become less stable when SG does. This is justified by the appearance of WECS to the system as a voltage source behind impedance and does not interface with the network through an internal angle like SG. [35]

Having been familiar with the impacts of WECS on the stability of electrical power systems, it is good now to look at system stability enhancement techniques adopted in the literature. One important technique used for WECS stabilization is the use of FACTS devices. Another possible way for stabilization is the use of voltage and/or frequency controls.

2.5.2 STATCOM Applications in WECS

The performance of STATCOM is compared against capacitive bank compensation for reactive power compensation applications in a single machine infinite bus system [62]. From the results it is observed that with STATCOM the oscillations are reduced as compared to the capacitive bank. Furthermore, voltage dip and critical clearing time are improved with the STATCOM than with capacitive compensation.

Static reactive compensator (STATCOM) based on voltage source converter (VSC) to stabilize grid connected FSWTG is proposed in [62-63]. Proportional - Integral (PI) control and Fuzzy logic control (FLC) is used to control the STATCOM. Results prove that fuzzy logic controlled STATCOM gives better response that PI controlled ones. In addition, it is shown that WECS equipped with Fuzzy Logic Controlled STATCOM is transiently more stable than WECS equipped with pitch controller only.

2.5.3 Software Packages Used in Stability Problems

The WECS models and their control schemes must be developed in a way to fit current simulation packages in order to ease the integration of those models with electrical power systems models. Simulations are found to be performed in the literature using Power System Toolbox of Matlab, Real Time Digital Simulator (RTDS), Power System Simulator for Engineers (PSS/E), PSCAD/EMTDC and others.

CHAPTER 3

MATHEMATICAL FORMULATION AND OPTIMIZATION SOLUTION ALGORITHM

3.1. Problem Description

The problem of power system stability is an ongoing field of study that was recognized in the 1920s and continued ever since. Early stability problems were associated with simple systems in terms of magnitude of electrical power systems at that time and in terms of dynamic models used to represent different components in that system.

Nowadays, several advances in the technologies used in the operation of electrical power systems, such as controllers, excitation systems and FACTS devices, led to a more complicated problem where detailed modeling of each component must be thoroughly developed to ensure proper representation in stability analysis.

Power system stability problem is classified into more than one problem in order to ease its analysis and understanding and transient stability is one of the classes. Transient stability is the ability of electrical power systems to stay in synchronism after large disturbances. Transients in an electrical power system could be from a loss of one machine, short circuits in transmission lines, or sudden changes in loads. The time frame of interest in transient stability studies is usually 3 to 5 second after the disturbance [56]. This work deals entirely with the transient stability problem of electrical power systems.

Recent trends of opening electricity markets to competition worldwide and introducing new forms of generations, especially from renewable resources, are putting increasing amounts of stresses on the existing systems. They are, in addition to that, moving the operating points even closer to stability limits. This in turn is giving a better chance for systems instabilities to occur. When they are installed in small quantities and dispersed throughout the grid, their impact might be neglected. This is not the case when their presence in the system dominates and reaches high levels.

In order to fully analyze DG impacts on stability, several points must be taken into account. First of all, the technology of DG and its associated controllers must be well modeled. Second, the penetration levels are to be investigated since system instability is a function of DG contribution to the system. Finally, DG units may come in small sizes where they are only installed at the distribution levels of the electrical power systems making them electrically far away from conventional generation units. Hence, their location within the system is to be investigated as well.

Proposed solutions in order to minimize the impact of WECS presence within an electrical power system are proposed. Some of them include the utilization of STATCOM in order to regulate induction generator's terminal voltage and Power System Stabilizers for damping of synchronous generators oscillations. The design of PSS and STATCOM parameters is considered as an optimization problem and GA is used for searching optimized parameters.

3.2. Modeling and Mathematical Formulation

3.2.1 Overview:

This section describes models used in transient stability time domain simulations. They are all developed in MATLAB/SIMULINK environment using SimPowerSystems® blocks library. This library provides a wide variety of ready-made models for synchronous/asynchronous machines, transformers, FACTS devices, control blocks, and prime movers from which you can easily drag and drop required blocks and build up the model to be analyzed. It also contains basic system components from which users can develop their own models. It features simplicity in addition to fast and accurate simulation performances. This MATLAB/SIMULINK tool has been used frequently in the literature such as [75-79].

3.2.2 Synchronous Generators (SG)

Dynamic models used for synchronous generators in this study are Round Rotor synchronous machines. The electrical part of the machine is represented by a sixth-order state-space model and it is widely used in the literature [46]. Mathematical representations of synchronous generators are expressed by the following set of equations:

$$V_d = R_S i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \tag{3.1}$$

$$V_q = R_S i_q + \frac{d}{dt}\varphi_q - \omega_R \varphi_d \tag{3.2}$$

$$V'_{fd} = R'_{fd}\, i'_{fd} + \frac{d}{dt}\varphi'_{fd} \tag{3.3}$$

$$V'_{kd} = R'_{kd}\, i'_{kd} + \frac{d}{dt}\varphi'_{kd} \tag{3.4}$$

$$V'_{kq1} = R'_{kq1}\, i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \tag{3.5}$$

$$V'_{kq2} = R'_{kq2}\, i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \tag{3.6}$$

$$\varphi_d = L_{id}\, i_d + L_{md}\,(i'_{fd} + i'_{kd}) \tag{3.7}$$

$$\varphi_q = L_q i_q + L_{mq} i'_{kq} \tag{3.8}$$

$$\varphi'_{fd} = L'_{fd}\, i'_{fd} + L_{md}\,(i_d + i'_{kd}) \tag{3.9}$$

$$\varphi'_{kd} = L'_{kd}\, i'_{kd} + L_{md}\,(i_d + i'_{fd}) \tag{3.10}$$

$$\varphi'_{kq1} = L'_{kq1}\, i'_{kq1} + L_{mq}\, i_q \tag{3.11}$$

$$\varphi'_{kq2} = L'_{kq2}\, i'_{kq2} + L_{mq}\, i_q \tag{3.12}$$

Where,

d, q	direct axis and quadrature axis quantities
r, s	rotor and stator quantities
l, m	leakage and magnetizing inductance
f, k	Field and damper winding quantities

In contrast, the regulator and prime mover dynamics are not taken into account in the transient simulations and the mechanical input to the machine is assumed to be constant throughout simulations period.

3.2.3 Excitation System

The synchronous machines are equipped with an excitation system that uses IEEE type-1 voltage regulator combined with an exciter. Its purpose in this work is to control the terminal voltage of the synchronous machines at a specified reference voltage. The mathematical model used in this study is available at [13] and depicted in the following figure.

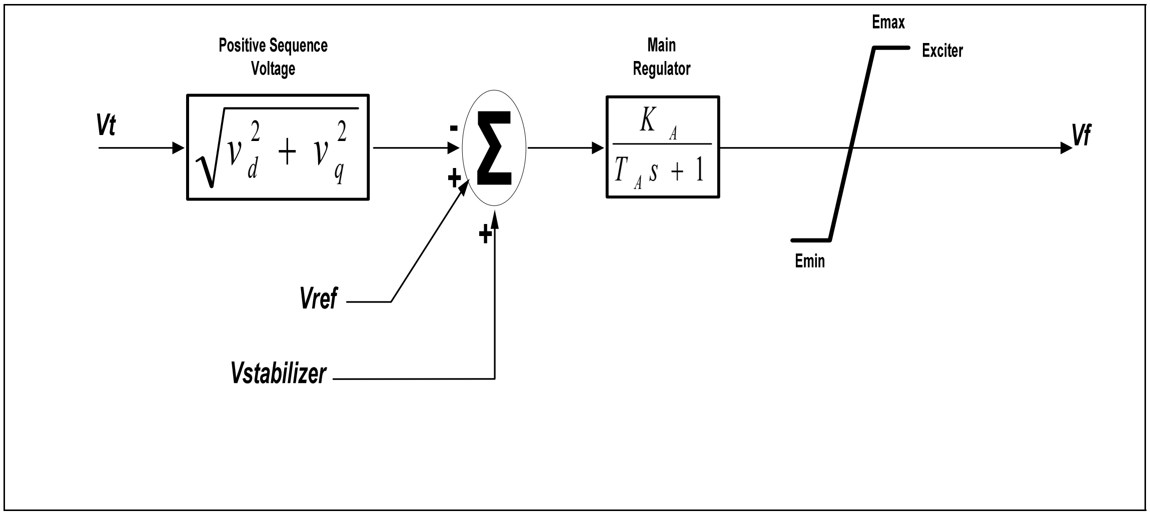

Figure 3.1: IEEE Type-1 Voltage Regulator with Exciter

Where,

v_t	Machine's terminal voltage
v_d	d-component of the terminal voltage in pu
v_q	q-component of the terminal voltage in pu
K_A, T_A	Regulator gain and time constant
v_{ref}	Reference voltage value in pu to control at
$v_{stabilizer}$	PSS input signal
v_f	Exciter field voltage supplied to the synchronous machine

3.2.4 Power System Stabilizer Model

Power system stabilizers (PSS) are being used as a supplementary excitation control for the sake of improving system stability by adding damping to generator rotor oscillations. For this purpose, generator excitation is modulated based on variations in an input signal which can be rotor speed, power or frequency. It has been proved that selection of PSS parameters has a great effect on the stability. [13, 73]

A conventional PSS based on rotor speed deviation is used in this thesis. It is composed of three main blocks, namely, the gain block, the high-pass filter block, and the phase compensation block. It can be mathematically formulated as:

$$U = K \frac{sT_w}{1 + sT_w} \frac{1 + sT_1}{1 + sT_2} \frac{1 + sT_3}{1 + sT_4} \Delta \omega \tag{3.13}$$

The gain block, specified by the constant K, determines the amount of damping introduced by PSS. This constant should be set to achieve maximum oscillation damping required. In some situations, the absence of this block, i.e. K = 0, instability may occur.

The signal washout block, also known as high-pass filter block, reacts to oscillations in rotor speed only. T_w is the washout time constant.

The phase compensation block, composed of one or more first-order blocks, provides compensation for the phase lag between the exciter input and electrical torque of the generators. In this thesis, two first-order lead lag blocks are implemented.

3.2.5 Wind Energy Conversion Systems (WECS)

Overview: The wind turbine induction generator model is a squirrel cage induction generator directly coupled to the grid. Fixed speed wind turbines can deliver maximum power out of wind at a single and specific wind speed, for example 12 m/s. For this reason, FSWT are usually equipped with pitch-control for maximum wind power extraction. Another purpose of pitch-control is to limit power conversion in case of high wind speeds. The following paragraphs will detail every component apart.

Wind Turbine Model: Wind turbines (WT) are defined as the mechanical systems that are designed to convert kinetic energy stored in the wind to a useful mechanical energy. This mechanical energy is in turn used to drive electrical machines, either synchronous or asynchronous generators.

Figure 3.1 shows block diagram for the wind turbine model developed in MATLAB/SIMULINK. The mechanical power out of the wind turbine can be generally expressed by the well-known output power to wind speed relationship as:

$$P_w = \frac{1}{2} c_p(\lambda, \beta)\rho A v_{wind}^3 \tag{3.14}$$

Where,

P_w	Mechanical output power of the turbine (W)
c_p	Performance coefficient of the turbine
ρ	Air density (kg/m3)
A	Turbine swept area (m2)
v_{wind}	Wind speed (m/s)
λ	Tip speed ratio of the rotor blade tip speed to wind speed
β	Blade pitch angle (deg)

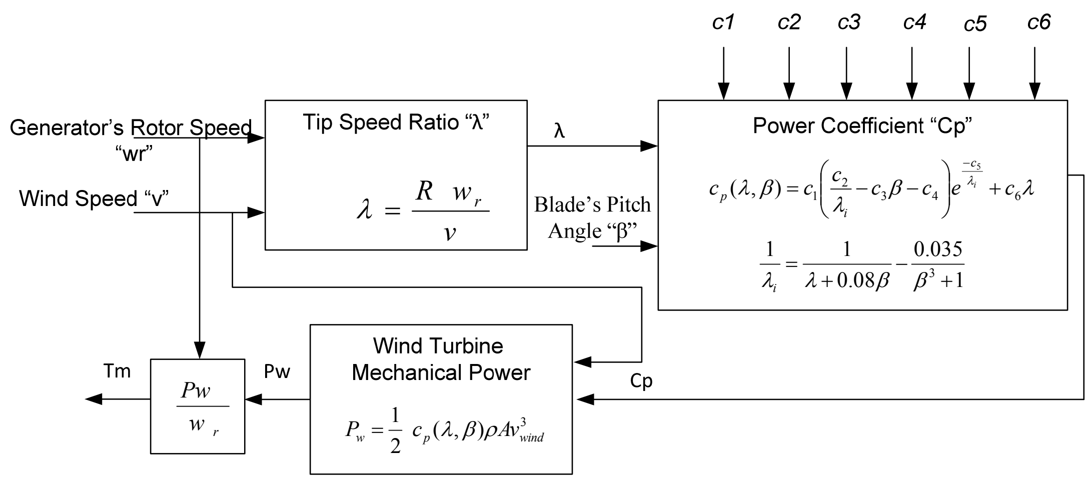

Figure 3.2: Block Diagram for Wind Turbine Model

The performance coefficient (C_p) defines the ratio between extracted power to the available power in the wind. It is a function of the change in the pitch angle of a wind turbine as well as tip speed ratio. A typical performance curve is depicted in figure 3.2.

The value of C_p is highly nonlinear and varies with the wind speed, the rotational speed of the turbine, and the turbine blade parameters such as pitch angle. It can be calculated from:

$$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{3.15}$$

Where the coefficients used for a typical model are given by [23]:

$C_1 = 0.51176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$

And,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.16}$$

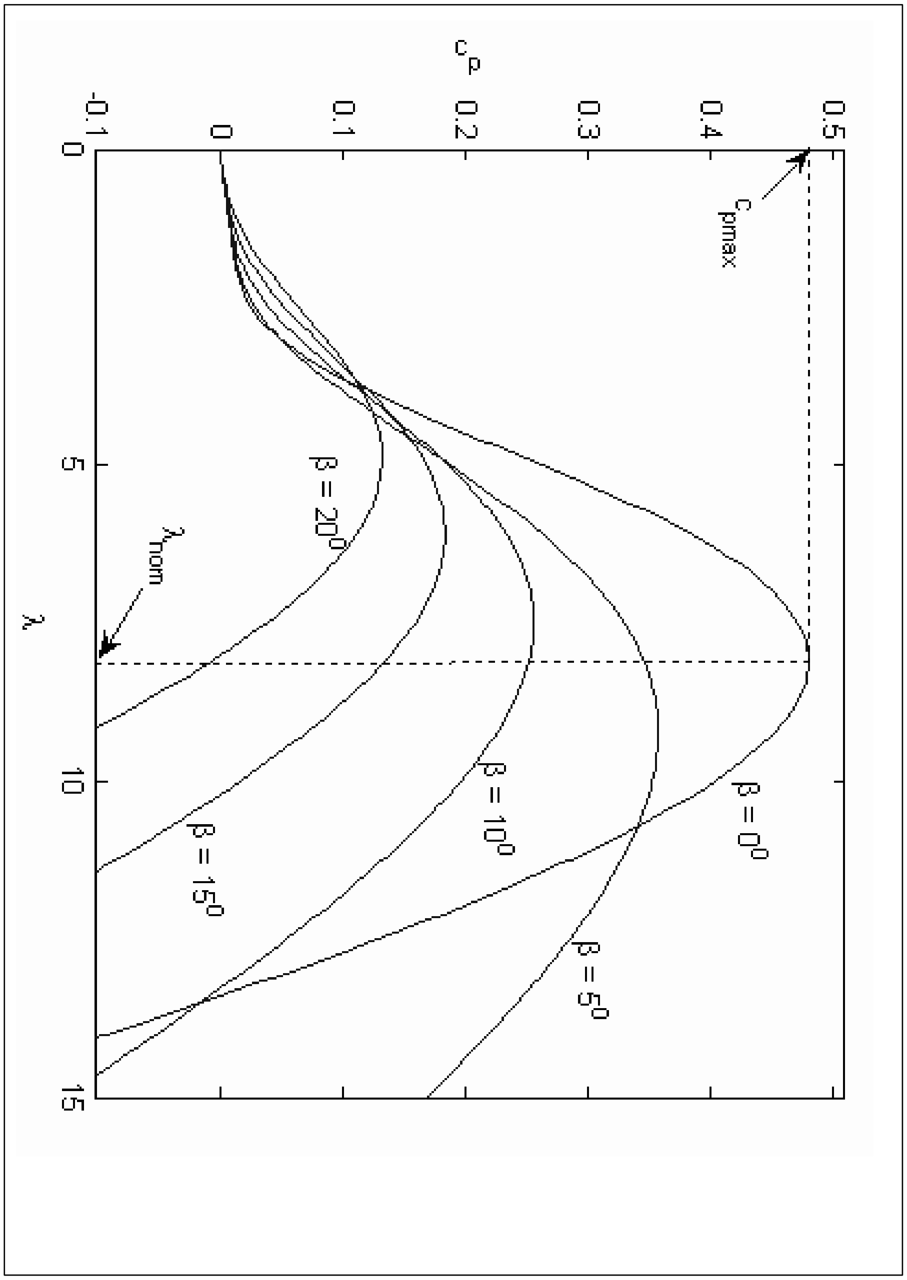

Figure 3.3: Cp-λ Curve for Different Pitch Angle Values

Tip speed ratio (λ) is the ratio of a turbine blade's tip speed to wind velocity. Given the wind turbines' blades radius (R), Rotor speed (w_r) and wind speed (v), then the tip speed ratio is:

$$\lambda = \frac{R \ w_r}{v_{wind}} \tag{3.17}$$

It can be noticed that from figure 3.2 the maximum C_p obtained and therefore maximum extracted power from wind for a given wind turbine geometry is achieved when the pitch angle is at zero degrees ($\beta = 0$). At this point, tip speed ration is known to be nominal (λ_i).

The output mechanical power of a fixed speed wind turbines (FSWT) run at a rated and pre-specified wind speed. They deliver rated mechanical power at this speed when pitch angle is zero. They can, in addition, deliver more than the rated mechanical power at higher wind speeds and must be equipped with pitch controllers in order to manipulate output power of a wind turbine. Figure 3.3 shows mechanical output power curves for a wind turbine at different wind speeds.

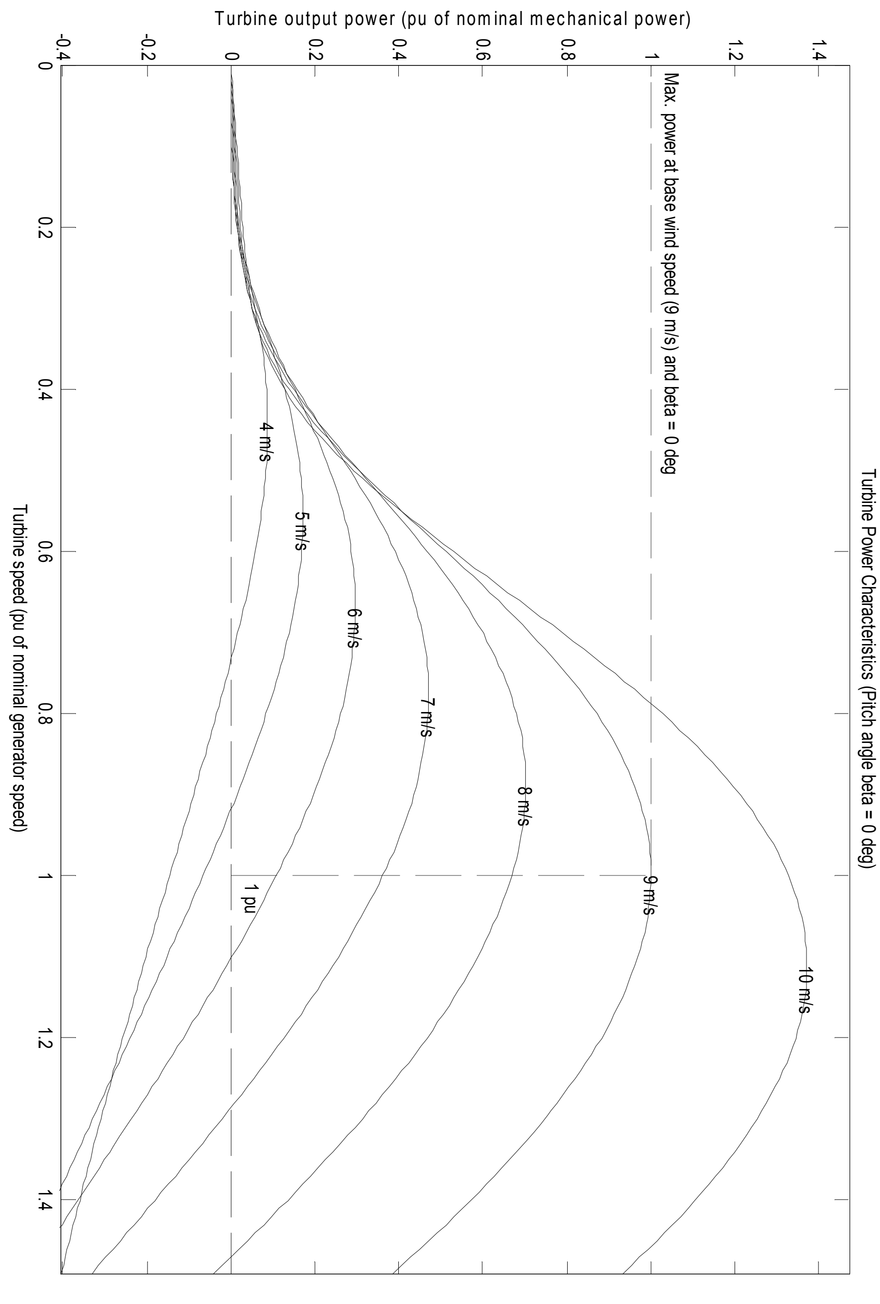

Figure 3.4: Wind Turbine Mechanical Output Power at Different Wind Speeds (β = 0)

<u>Pitch Angle Control System:</u> Pitch angle control used in this research is depicted in the figure 3.4. The control input signal for such controller is P_e/V_t^2, where P_e is the output active power and V_t is the induction generator's terminal voltage. Reference signal is the quantity to be controlled and it is chosen in this study to be the active power (P_e). The error between the reference power and the controlled signal (β_{ref}) is compared to the actual pitch angle (β). The initial pitch angle value (β_0) is set to 0°. It is then fed to a hydraulic servo controller with time delay constant, T_{servo} = 0.0025 sec. this time constant is adjusted for best performance. Further, the pitch angle rate of change ($\frac{d\beta}{dt}$) is limited by ±5 degree/s, which is the typical value for pitch control wind turbines. The pitch angle is set to be in the range of 0° - 45°.

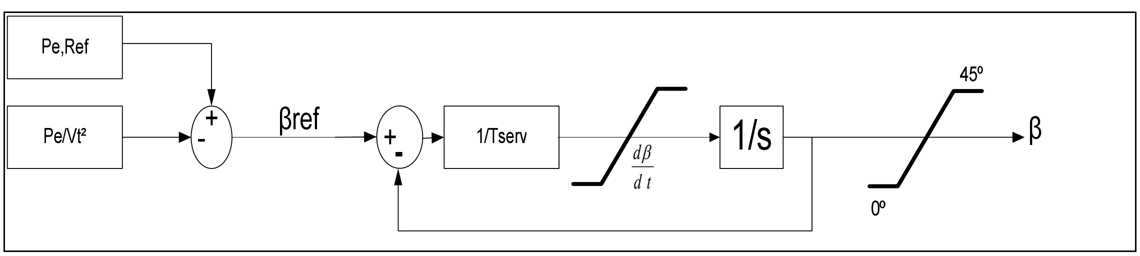

Figure 3.5: Pitch Angle Control Scheme

Induction generators: Induction generators used in this research are Squirrel Cage Induction Generators (SCIG) that are directly couple to the grid. Due to their simplicity and wide availability, SCIG are mostly used in WECS applications.

They are mathematically represented by a fourth order state-space model as in the following set of equations:

$$V_{qs} = R_s i_{qs} + d/dt\, \varphi_{qs} + \omega\varphi_{ds} \quad (3.18)$$

$$V_{ds} = R_s i_{ds} + d/dt\, \varphi_{ds} + \omega\varphi_{qs} \quad (3.19)$$

$$V_{qr} = R_r i_{qr} + d/dt\, \varphi_{qr} + (\omega - \omega_r)\, \varphi_{dr} \quad (3.20)$$

$$V_{dr} = R_r i_{dr} + d/dt\, \varphi_{dr} + (\omega - \omega_r)\, \varphi_{qr} \quad (3.21)$$

$$T_e = 1.5p(\varphi_{ds}\, i_{qs} - \varphi_{qs}\, i_{ds} \quad (3.22)$$

Where,

$$\varphi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{3.23}$$

$$\varphi_{ds} = L_s i_{ds} + L_m i_{dr} \tag{3.24}$$

$$\varphi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.25}$$

$$\varphi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.26}$$

$$Ls_s = L_{ls} + L_m \tag{3.27}$$

$$Ls_r = L_{lr} + L_m \tag{3.28}$$

Induction generator parameters used in the time domain dynamic simulations are illustrated in the next chapter.

Shaft system: The shaft system, known also as drive train in the literature, is the component of WECS that is responsible for transferring the mechanical energy captured from wind to the generator shaft. It is represented in the dynamic analysis as a lumped mass system where turbine, gearbox, and generator rotors' inertias are summed together. It is expressed in mathematical format as:

$$2H_L \frac{dw_r}{dt} = T_M - T_E - F_L w_r \tag{3.29}$$

Where,

w_r	Rotational System of lumped-mass System.
H_L	Lumped inertia constant of the shaft system
F_L	Damping coefficient of the lumped system
T_M	Mechanical Torque of wind turbine rotor
T_E	Electrical torque of the induction generator

Figure 3.5 depicts the block diagram representation of the shaft system.

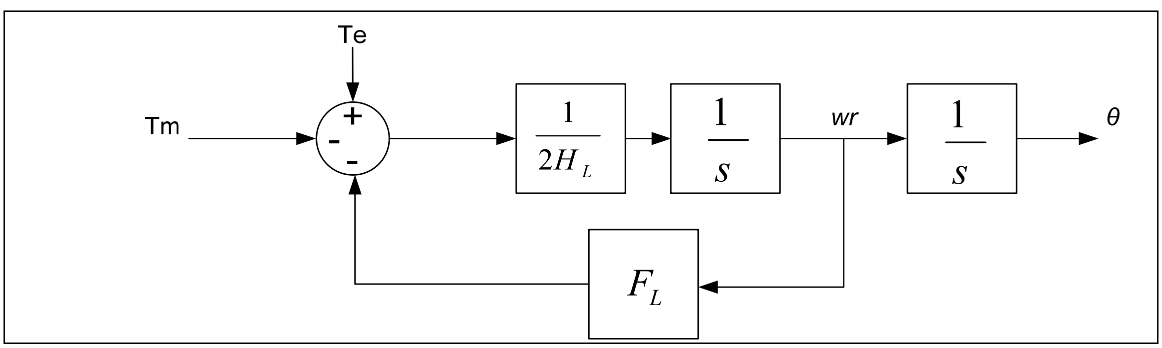

Figure 3.6: Block Diagram for the Shaft System

3.2.6 Static Synchronous Compensator (STATCOM) Model:

Static Synchronous Compensator, or shortly STATCOM, is one of the means that are validated for electrical power systems stability enhancement applications [62-72]. It was proven better in improving system's stability than static capacitor banks and SVC. Its control scheme is also playing a vital role in system's stability. So, STATCOM will be used and modeled for the sake of improving the multi-machine electrical power system.

STATCOMs are one of flexible AC transmission system (FACTS) devices that are based on voltage source converters (VSC). They are shunted to wind turbine generators for the purpose of voltage control by manipulating the amount of reactive power injected into or absorbed from the grid. On one hand, STATCOM generates reactive power when system voltage is low (STATCOM capacitive). On the other hand, it absorbs reactive power when system voltage is high (STATCOM inductive).
According to [69], there are three potential locations for STATCOM in a wind farm application. It could be at the transmission level (serving several wind farms), at the distribution level (at medium voltage, serving a single wind farm) and at low voltage level (serving individual wind turbines). Accordingly, there are three main STATCOM technologies: transmission, distribution and low voltage with the fact that

the distribution STATCOM, connected to the wind farm substation and serving a single wind farm, seems to be the most interesting solution, implemented with MV or LV (with transformer) technology.

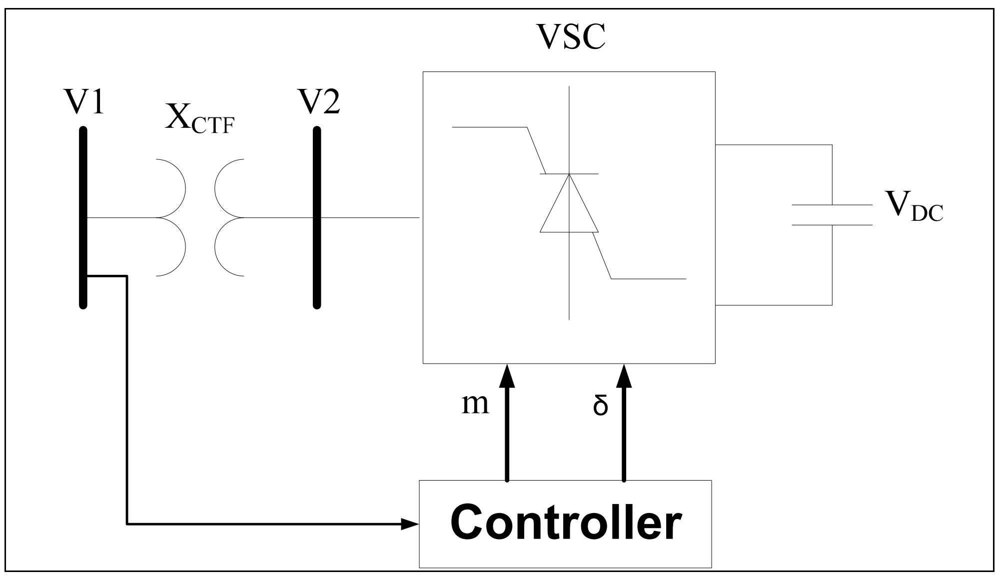

Figure 3.7: STATCOM Overall Model

In figure 3.6, STATCOM model is composed of a coupling transformer by which the STATCOM is interfaced with the grid. The transformer's leakage reactance is denoted by X_{CTF}. Another component is a VSC that is based on GTO for voltage generation V2 from DC voltage source V_{DC}. A capacitor bank connected on the DC side of the VSC is used as a DC voltage source. The variation of the voltage generated by STATCOM output voltage (V2) and the grid voltage (V1) allows effective power exchange between STATCOM and the grid. This exchange is controlled by adjusting STATCOM voltage phase (δ) and magnitude (m).

<u>STATCOM Dynamic Model:</u> Given the three phase voltages (v_a, v_b, v_c) and currents (i_a, i_b, i_c), the dynamic model of STATCOM can be expressed as:

$$v_d = R_{ST} i_d + L_{ST} \frac{di_d}{dt} - w_e L_{ST} i_q + v_{sd} \tag{3.30}$$

$$v_q = R_{ST} i_q + L_{ST} \frac{di_q}{dt} - w_e L_{ST} i_q + v_{sq} \tag{3.31}$$

Where,

R_{ST} ,L_{ST}	STATCOM's convertor impedance
d,q	direct and quadrature components
v_s	system voltage

And if we assumed zero power losses, the instantaneous power balance between AC and DC sides will result in:

$$v_{dc}i_{dc} = v_a i_a + v_b i_b + v_c i_c \tag{3.32}$$

$$C_{ST} v_{dc} \frac{dv_{dc}}{dt} = \frac{3}{2}\left(i_d v_{sd} + i_q v_{sq}\right) \tag{3.33}$$

Where C_{ST} is the STATCOM capacitor.

Assuming correct alignment of the rotating reference frame, then v_{sq} *can* be considered zero, and therefore,

$$\frac{dv_{dc}}{dt} = \frac{3 \times i_d v_{sd}}{2 \times C_{ST} v_{dc}} \tag{3.34}$$

Equation (3.32) shows that the DC bus voltage can be maintained constant by controlling the d−component of STATCOM current, i_d. The instantaneous STATCOM reactive power (Q_{ST}) is calculated by equation (3.33). Assuming reactive power

$$Q_{ST} = \frac{3}{2} i_q v_{sd} \tag{3.35}$$

Assuming reactive power balance at PCC,

$$v_{sd} = \frac{X_l X_{TF}}{X_l + X_{TF} - X_l X_{TF} B_C} i_q + \frac{X_l v_{2d} + X_{TF} v_{1d}}{X_l + X_{TF} - X_l X_{TF} B_C} \tag{3.36}$$

Equation 3.31 and 3.34 show that the DC bus voltage v_{dc}, and the AC system voltage v_s, can be regulated by the d−component and q−component of STATCOM currents, respectively.

<u>STATCOM Control Scheme:</u> A three-level PWM based STATCOM is connected with wind farm terminal. PI controllers are used for the internal AC and DC voltage control. The STATCOM control strategy is depicted in figure 3.7. It consists of phase locked loop, two measurement systems, current, AC voltage and DC voltage controllers.

The phase locked loop is used for providing synchronous reference (θ) required by abc/dq transformation. The measurement blocks compute d-axis and q-axis components of the AC voltage and current (V_d, V_q and I_d, I_q). Those are the variables to be controlled. Also to be controlled is the DC voltage (v_{dc}).

An outer regulation loop consists of AC and DC voltage controllers. The output of the AC voltage controller is the reference current (I_{qref}) for the current controller, which controls reactive power flow. The output of the DC voltage regulator is the reference current (I_{dref}) for the current controller, which controls active power flow. I_{qref} and I_{dref}, which are produced from AC and DC voltage controllers, respectively, are fed to a current controller. This controller regulates both the magnitude and phase of the voltage generated by the PWM converter (V_{2d} V_{2q}).

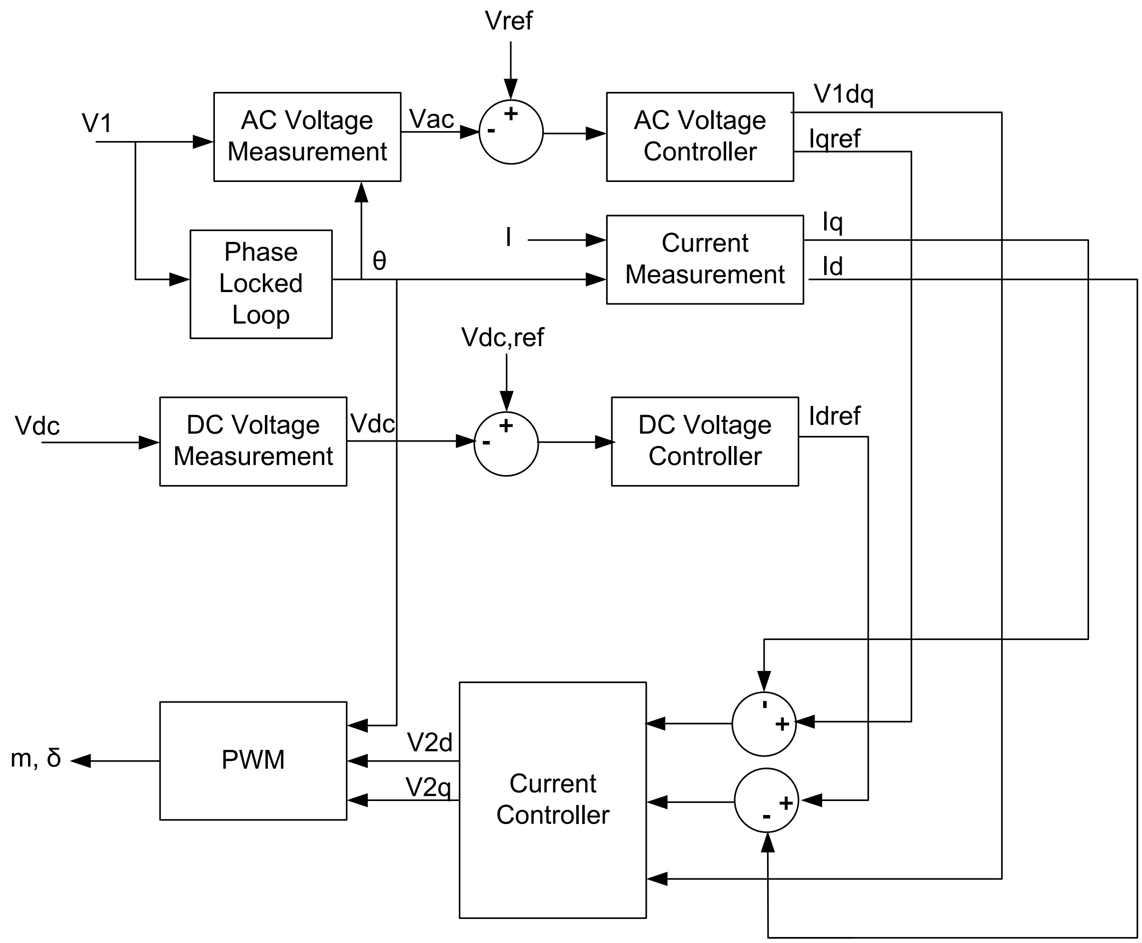

Figure 3.8: STATCOM Control Scheme

STATCOM AC and DC Voltage Controllers: AC and DC voltage controllers are using classical PI controllers in order to regulate the output reference signals (I_{dref} and I_{qref}) when AC or DC voltages deviate from their reference values. They are shown in the following two figures where $K_{p,ac}$ and $K_{i,ac}$ are the AC voltage controllers' proportional gain and integral time constant, respectively. Similarly, $K_{p,dc}$ and $K_{i,dc}$ are the DC voltage controllers' proportional gain and integral time constant. This controller have been widely used in the literature and its effectiveness has been observed [63, 68].

These parameters are the design problem to be solved for optimum STATCOM control. Details about the solution methodology are found in solution algorithm section of this chapter. Optimum solution parameters are calculated and presented in chapter 5.

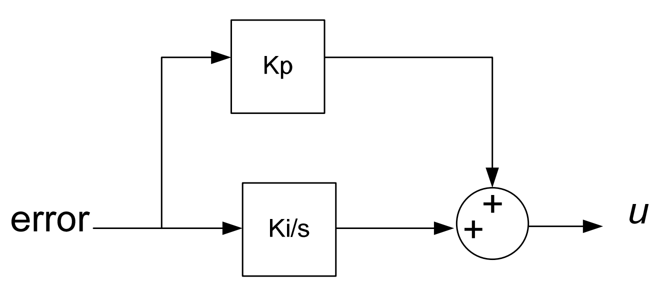

Figure 3.9: STATCOM AC/DC Voltage PI Controller

3.2.7 Wind Farm Representation:

The wind farm (WF) presented in this thesis is composed of a number of identical wind turbines driving identical induction generators. In parallel with each wind turbine induction generator, a shunt capacitance bank is installed in order to compensate for no-load reactive power. The value of shunt compensation bank is calculated so that it will provide more than 90% of reactive power required by the induction generation units [60].

Each WTG unit's terminal voltage is stepped-up by a transformer. WTG units are scattered in nature and must be coupled together at the so-called collector bus via short transmission lines. Collector bus voltage is stepped-up to nominal transmission line voltages. The wind farm is connected to the main system at load buses.

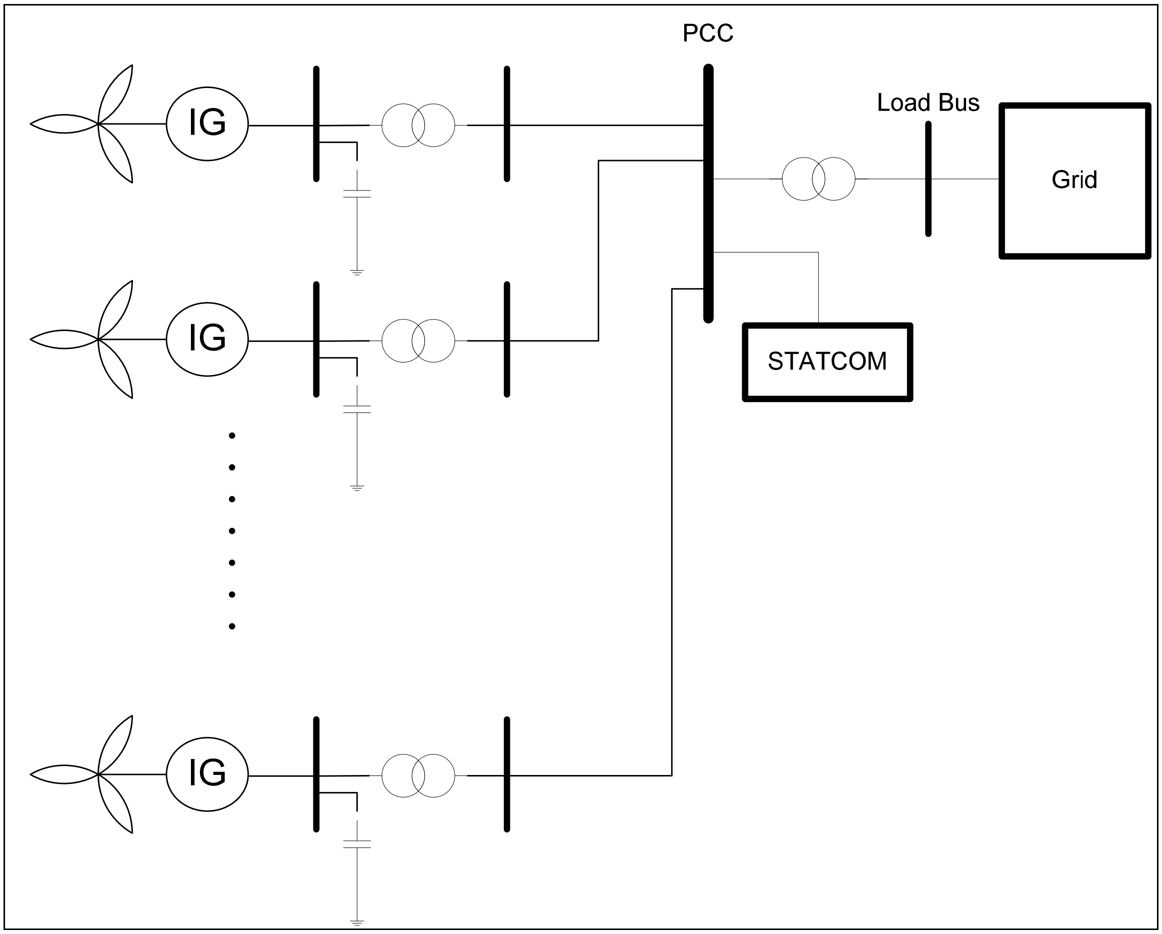

Figure 3.10: Distributed Model of a Wind Farm Connected to the Grid

3.3. Optimization and Solution Algorithm

3.3.1. Overview

It was mentioned earlier that there are three main factors influencing the stability of an electrical power system having DG units connected to it. They are the type of DG technology, penetrations level and location within the system. In order to analyze the stability problem of an electrical power system in the presence of a DG technology, different scenarios are to be simulated in terms of those factors.

3.3.2 DG Technology

Since this thesis is dedicated to analyze of WECS as a good technology candidate for DG, simulations are carried out using the model of WECS illustrated in the previous sections.

3.3.3 DG Penetration Levels

Secondly, different penetration levels of DG are to be examined. The penetration level is meant by the amount of active power delivered by WECS, and thus keeping total active power generated within the system same. It is scaled in percentage of total generation. In this work, it is assumed that the maximum penetration level that a DG can contribute to an electrical power system is 30% of the system's total generation.

This is due to the fact that increasing generation capacity of a DG unit beyond this level will become unrealistic [16].

3.3.4 DG Location

Thirdly, the location where DG is embedded in the grid has its impact on the stability. Hence, the impact of WECS location is investigated at different buses. In fact, DG are almost always installed near to load buses since they have no environmental impact, so small in size that they are located at distribution levels, and sometimes dedicated for a specific customer. Impacts due to DG locations are studied where they are installed at load buses of a given system.

3.3.5. Power System Stability Performance Index

In order to numerically analysis the impacts on stability of an electrical power system under different scenarios of operations and disturbances, a performance index is adapted in this thesis. This index reflects a quantity's fluctuation settling time and percent overshoot of a single machine following a disturbance. All system machines' performance index is then summed up to reflect total performance of the system. [73]

The index is defined as:

$$PI_{system} = \sum_{i=1}^{n} \int_{0}^{tsim} (t \, \Delta \omega_i)^2 \, dt \tag{3.37}$$

Where,

PI	performance index
n	number of machines
tsim	simulation time
$\Delta\omega_i$	Rotor speed deviation in per unit
t	time at which speed deviation is measured

As might be observed from the above expression, this performance index value, if small, reflects a more stable system. On the other hand, higher values indicate a less stable system. Therefore, the problem of power system stability is to be solved in this work by minimizing this index.

A number of solutions to improve stability of an electrical power system with the presence of WECS are proposed in the literature [62-76]. In this thesis, the proposal of wind turbines terminal voltage regulation using STATCOM is used to improve transient stability of electrical power system. Another proposal used in this thesis is to model and design parameters of a power system stabilizer (PSS) to be used for improving synchronous generators stability. The next two sections will describe the proposed solution methodologies to design parameters of both STATCOM controller and PSS.

3.4. Tuning of STATCOM and PSS Control Parameters Using Genetic Algorithm

3.4.1. Overview:

Pre-specified control parameters have been used for STATCOM Proportional-Integral (PI) controller and PSS Lead-Lag (LL) controller. Because of the fact that control systems are time-varying and non-linear in nature, tuning the control parameters of a given controller is essential. There are a lot of methods about controller parameters tuning have been proposed, and most of them are based on Artificial Intelligence Techniques (AI), such as Genetic Algorithm (GA), Tabu Search (TS), and Simulated Annealing (SA).

In this thesis, we use a simple GA optimization method proposed in [75] for optimizing control parameters of both STATCOM PI and PSS LL controllers. Genetic Algorithms are optimization techniques based on simulating the phenomena that takes place in the evolution of species and adapting it to an optimization problem. They were proposed by John Holland.

3.4.2. Population Initialization and Coding:

GA start with an initial population of individuals, which is generated either randomly or with domain specific knowledge or by any conventional tuning method to get a smaller search space such as Ziegler-Nichols experiential method [82]. Each individual (chromosome) consists of a data structure, and represents a possible solution in the search space of the problem.

3.4.3. Fitness Function Definition and Evaluation:

Usually, a problem-specific fitness function maps the representation of the chromosomes into fitness values. The fitness values measure the quality of the individual as an optimal solution. The definition of the fitness function is very crucial in getting good solutions for a problem. In our problem, the fitness function to be evaluated is the stability performance index in equation 3.35. It is to be minimized to indicate less stability impact. This index is general and targeted to improve the stability of the system as a whole and not individual performance index of each machine.

$$PI_{system} = \sum_{i=1}^{n} \int_{0}^{tsim} (t \, \Delta \omega_i)^2 \, dt \tag{3.38}$$

3.4.5. Selection, Crossover and Mutation:

Biology evolution is executing through crossover and mutation of chromosomes mainly. Genetic algorithms simulate the evolution process using genetic operator for population to get a new generation. The optimization procedure starts from a population of randomly chosen chromosomes and generates new populations applying the operators of selection, crossover and mutation.

Selection is the process of searching for some fine individuals from current population to be passed to the next generation according to fitness value of each individual. The main goal is to select the chromosomes with the best qualities for integration. The selection function used in this algorithm is stochastic uniform, which lays out a line in which each parent corresponds to a section of the line of length proportional to its scaled value. The algorithm moves along the line in steps of equal size. At each step, the algorithm allocates a parent from the section it lands on.

Crossover is to compose a pair with every two individuals of the population and exchange parts of the chromosomes by some probability (*Pc*). By combining the chromosomes of two individuals, new chromosomes are generated and integrated into the population.

Changing one or several gene values by some probability (*Pm*) for each individual of the population is called mutation. New individuals are generated in the population by mutation.

In the simple genetic algorithms, the following steps are performed:

1. Select the proper population size M, individual code length L, evolution generation number T, crossover probability Pc, mutation probability Pm and generate M stochastic individuals as an initial population $P(g)|g=0$.

2. Decoding and selecting.

3. Crossover operation.

4. Mutation operation.

5. If $g<G$, then $g=g+1$; and return to step 2; Otherwise, take current optimal individual as the optimal solution and stop.

Where (g) is the generation number, and (G) is the total generation number at which the algorithm will halt. It is 1500 in this thesis. The process in genetic algorithms is called a *generation*, and the entire set of generations is called a *run*. There are often one or more high fitness chromosomes in the population at the end of a run.

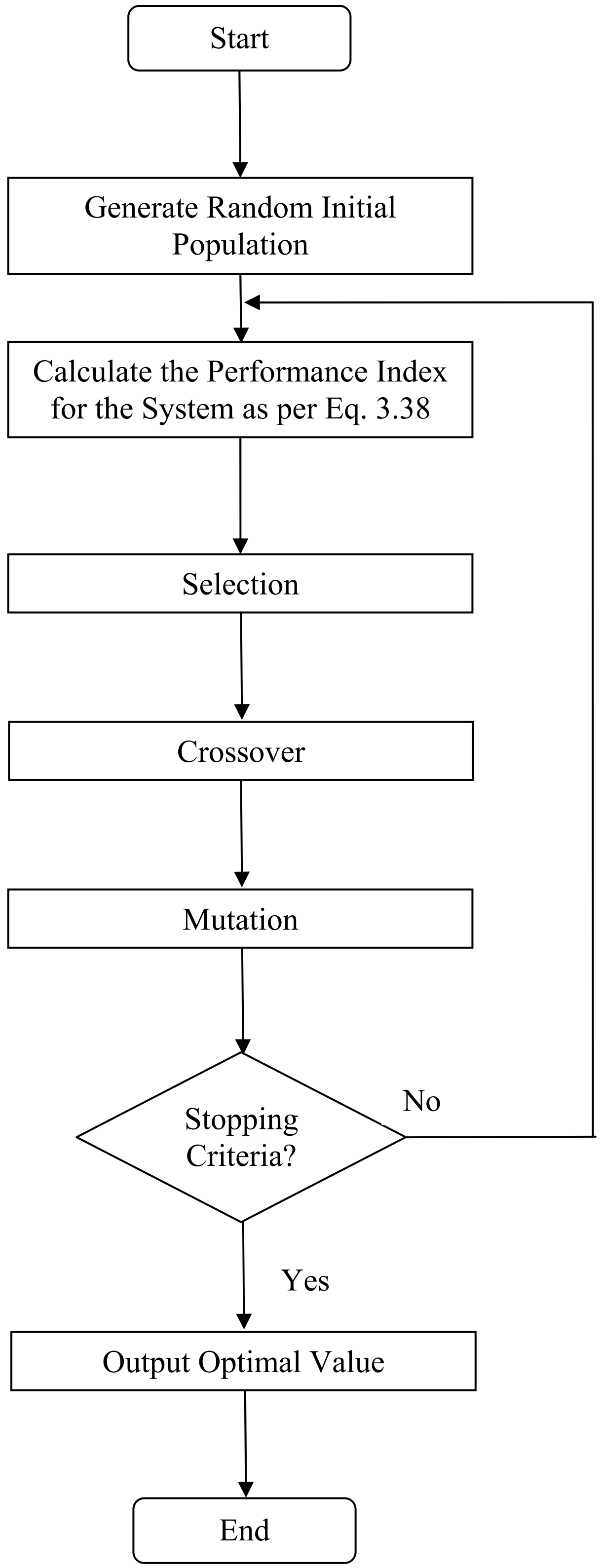

Figure 3.11: Flow Chart of Simple GA Technique

Chapter 4 will show simulation results when the dynamic models mentioned herein are used in non-linear time domain simulations for a multi-machine electrical power system. In chapter 5, tuning STATCOM PI controllers and PSS gain and time constants will be done in order to enhance stability of electrical power system.

CHAPTER 4

SIMULATION RESULTS: MULTIMACHINE ELECTRICAL POWER SYSTEM, WITH WECS

4.1 Introduction:

This chapter is dictated for time-domain simulations where stability performance of a multi-machine system is analyzed with WECS. The time-domain simulations and performance indices calculated herein will be used as a base case measure where no enhancements are introduced in the system. The results of this chapter will be used later for comparison purposes with other cases that will be discussed in chapter 5. Load flow calculations and time-domain transient simulations are carried out in MATLAB/SIMULINK environment.

4.2 Study Case Description:

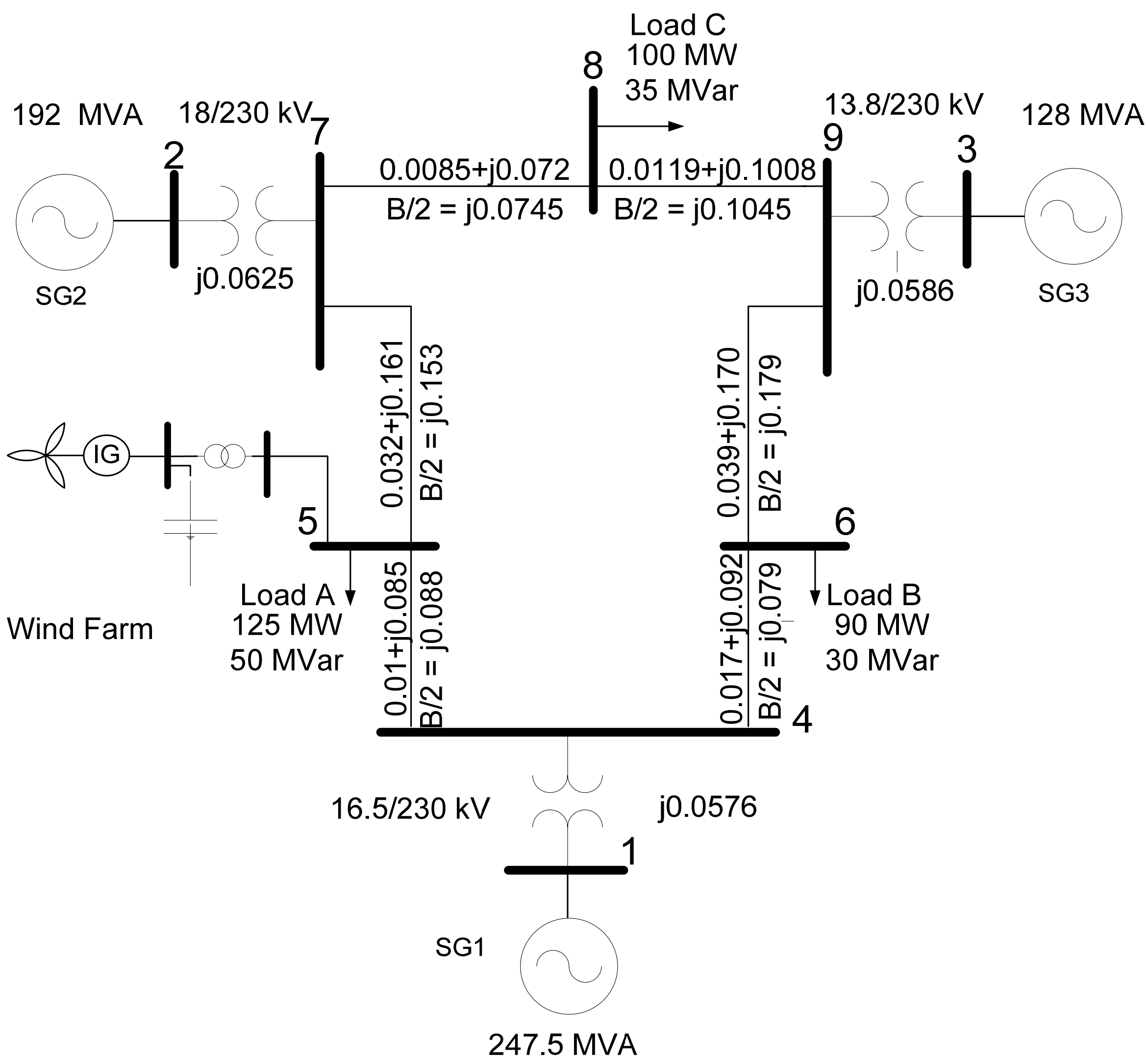

Figure 4.1: Nine Bus System with WECS at Load Bus 5

Figure 4.1 illustrates the multi-machine electrical power system used in the simulation analysis of this thesis. It is a nine bus system that has three synchronous generation units at buses 1, 2 and 3, three constant impedance loads at bus 5, 6 and 8, and nine branches. Wind farm, which is composed of a number of identical wind turbines and induction generators, is connected to the main system at load buses; one time it is connected at load bus 5 and another time at load bus 6. System synchronous and induction generators' parameters are listed in table 4.1 and 4.2, respectively.

Table 4.1: Synchronous Generators' Dynamic Parameters on 100 MVA Base

NO	Description	Unit	SG1	SG2	SG3
1	**T'do (>0)**	Sec	8.96	6	5.89
2	**T"do (>0)**	Sec	0.01	0.01	0.01
3	**T'qo (>0)**	Sec	0.01	0.535	0.6
4	**T"qo (>0)**	Sec	0.01	0.01	0.01
5	**Inertia, H**	sec	23.64	6.4	3.01
6	**Damping Factor, D**	-	0	0	0
7	**Xd**	p.u.	0.146	0.8958	1.3125
8	**Xq**	p.u.	0.0969	0.8645	1.2578
9	**X'd**	p.u.	0.0608	0.1198	0.1813
10	**X'q**	p.u.	0.0969	0.1969	0.25
11	**X"d = X"q**	p.u.	0.01	0.01	0.01
12	**Xl**	p.u.	0.0336	0.0521	0.0742

Table 4.2: Wind Turbine Induction Generator Dynamic Parameters

Squirrel Cage Induction Generator Parameter	**Value**
Nominal Power Base (MVA)	100
Voltage base (V)	575
Stator resistance Rs, (p.u.)	0.004843
Rotor resistance Rr, (p.u.)	0.004347
Stator leakage inductance Xs, (p.u.)	0.1248
Rotor leakage inductance Xr, (p.u.)	0.1791
Mutual inductance Xm (p.u.)	6.77
Per unit inertia constant of generator Hg (s)	5.04
Transformation reactance X, (p.u.)	0.025
A single transmission line reactance Xl (p.u.)	0.0013
Wind Turbine Parameter	**Value**
Nominal Power Base (MVA)	3
Min – Max Pitch Angle Limits (Degree)	0 – 45
Maximum Pitch Angle Rate of Change (Deg/sec)	5
Nominal Wind Speed (m/sec)	12

While bus number one is the reference bus, bus two and bus three are PV buses. Wind farm bus is considered as a PQ bus with negative load. That is, the induction machine is working as a generator delivering a fixed amount of mega watts.

The equivalent circuit of transmission lines is represented by a three phase PI circuit. The per-unit values illustrated in the above figure are converted to positive- and zero-sequence SI units. Table 4.3 shows transmission line parameters for the network under study. The loads are represented by constant impedances.

The nine bus system described in this section is simulated for four different operating scenarios, namely,

1. 30 MW WF connected at load bus 5.
2. 60 MW WF connected at load bus 5.
3. 30 MW WF connected at load bus 6.
4. 60 MW WF connected at load bus 6.

Table 4.3: Transmission Lines Impedances in per Unit and SI Ssytems

Branch		Line Impedances in PU			Line Impedances in SI			Line Impedances in SI		
From	To	**R**	**X**	**B/2**	**R**	**X**	**B/2**	**R (Ohm)**	**L (H)**	**C (F)**
4	**5**	0.0100	0.0850	0.0880	5.29	44.965	0.000166	5.29	1.19E-01	8.83E-07
4	**6**	0.0170	0.0920	0.0790	8.993	48.668	0.000149	8.993	1.29E-01	7.92E-07
5	**7**	0.0320	0.1610	0.1530	16.928	85.169	0.000289	16.928	2.26E-01	1.53E-06
6	**9**	0.0390	0.1700	0.1790	20.631	89.93	0.000338	20.631	2.39E-01	1.80E-06
7	**8**	0.0085	0.0720	0.0745	4.4965	38.088	0.000141	4.4965	1.01E-01	7.47E-07
8	**9**	0.0119	0.1008	0.1045	6.2951	53.3232	0.000198	6.2951	1.41E-01	1.05E-06

In order to investigate the dynamic performance of the system, a self-cleared three line to ground fault (LLLG) is applied near bus 7. The fault is applied at 1.0 seconds and cleared after 100 ms without tripping the faulted line. Fault impedance is 0.001 ohms. Wind speed is assumed to be constant at rated level of 12 m/sec during simulation period. This is because the variation of wind speed during the short time span of the analysis of transient stability can be considered negligible. The following sections will discuss simulation results of each scenario.

4.3 Simulation Results for the Nine Bus System with WF at Load Bus 5

In this section, non-linear time domain simulations are carried out for the nine bus system when wind farm is connected at load bus 5. Two wind farm ratings are considered, 30 MW and 60 MW. Machine initial conditions for these two scenarios are tabulated in table 4.4.

Table 4.4: Machine's Initial Conditions

Machine	Parameter	Scenario 1 30MW, WF5	Scenario 2 60MW, WF5
SG1	P	0.7055	0.6003
	V	1.04	1.04
	Theta	3.5	2.4
	Q	0.246	0.22
SG2	P	1.53	1.43
	V	1.025	1.025
	Theta	50.2	54.2
	Q	0.05207	0.03214
SG3	P	0.75	0.65
	V	1.025	1.025
	Theta	45.9	46.3
	Q	-0.1054	-0.1103
IG	P	0.2991	0.5972
	Q	0.1947	0.2812
	Slip	-0.001163	-0.002041

System responses for the applied fault are shown in figures 4.2 and 4.3. Figure 4.2 shows pre-fault and post-fault voltage drop and recovery at the terminals of the induction machine for two different wind farm ratings at load bus 5, 30 MW and 60 MW, respectively. Induction generator's terminal voltage was at 1.01 per unit before applying the fault. When the fault is applied, this voltage dropped to a minimum value of 0.64 as can be seen from the dashed line in the figure.

When a 60 MW wind farm is installed in the system at load bus 5, the terminal voltage of the induction generator was at steady state of 1.0 per unit. The voltage dropped to 0.625 when the fault is applied.

Following the clearance of the fault, the terminal voltage fluctuated around their steady state value. This fluctuation is noticed to be more severe with the 60 MW wind farm than the case with 30 MW wind farm.

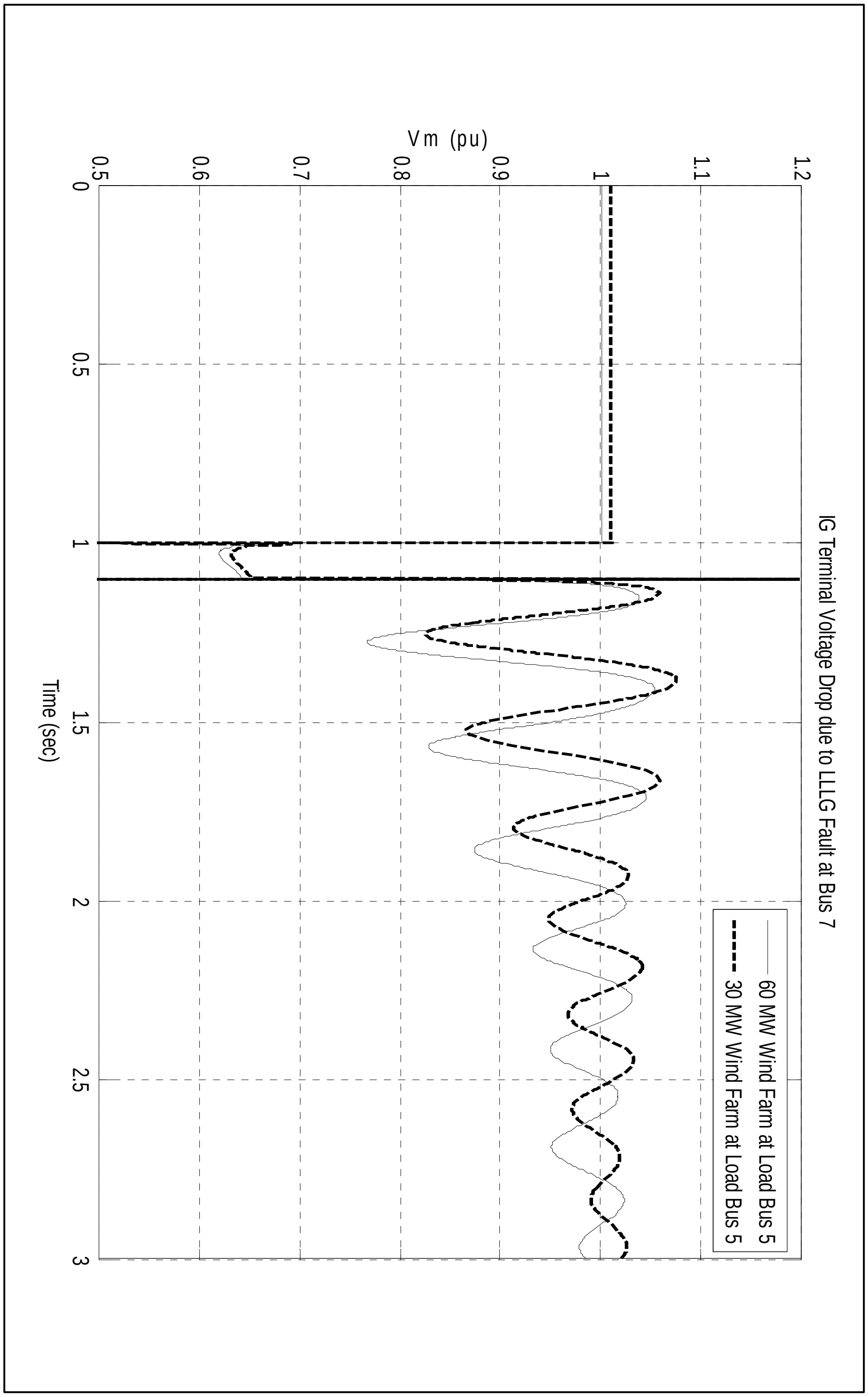

Figure 4.2: IG Terminal Voltage Drop due to LLLG Fault at Bus 7 without STATCOM and PSS

As a result of terminal voltage fluctuations observed in the above two cases, the corresponding induction generator's rotor speed deviations is observed following the fault. The rotor speed deviation, as shown in figure 4.3, is more sever with higher wind farm ratings. This is due to the fact that high terminal voltage drop leads to higher differences between the electromagnetic and mechanical torques applied by the wind turbine. This, in turn, results in worse induction generator rotor speed deviations.

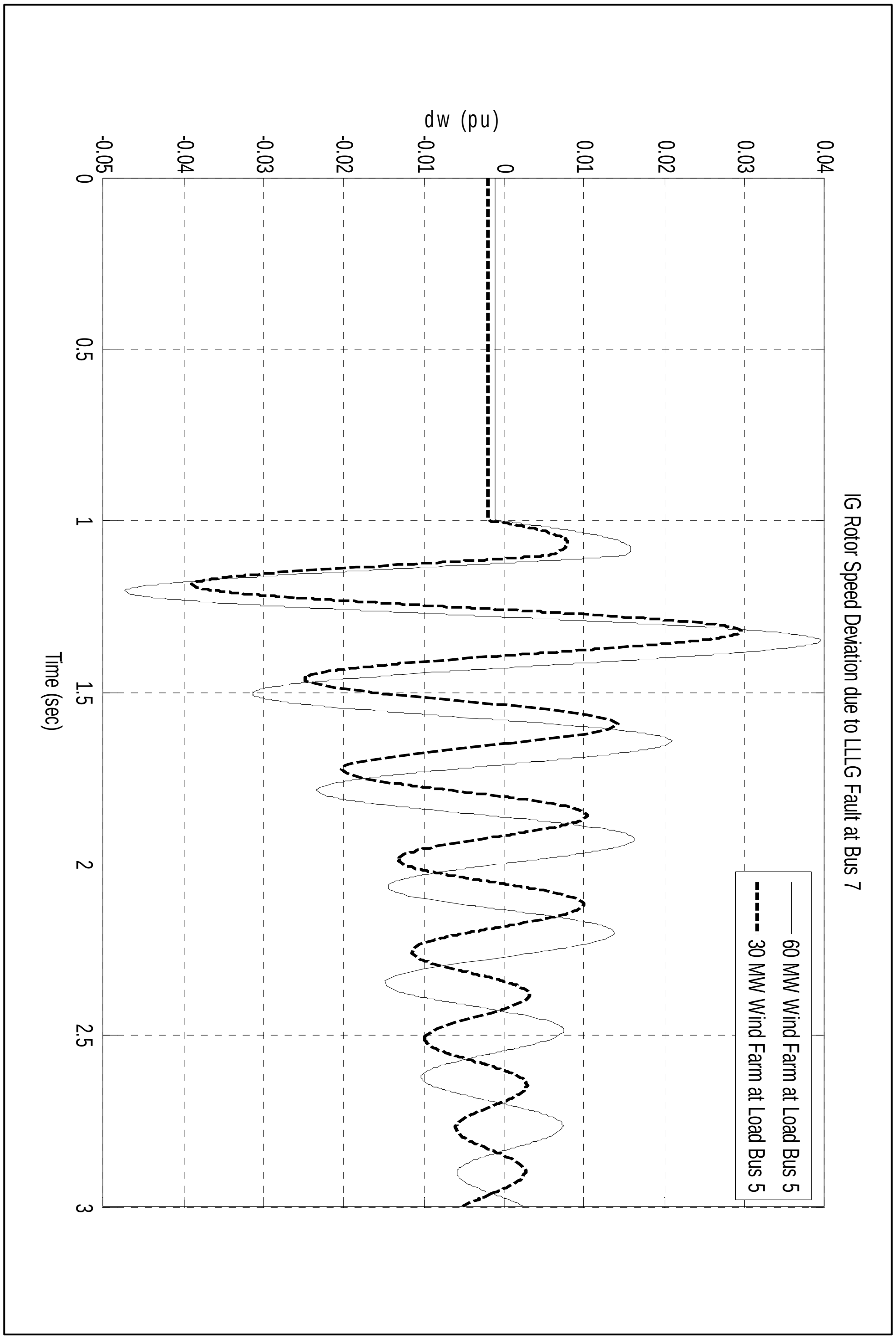

Figure 4.3: IG Rotor Speed Deviation due to LLLG Fault at Bus 7 without STATCOM and PSS

4.4 Simulation Results for the Nine Bus System with WF at Load Bus 6

Similar to the previous section where system dynamics were simulated when wind farm is connected at load bus 5, this section shows time-domain simulations for the system when wind farm is connected at load bus 6. Wind farm ratings, 30 MW and 60 MW, are also simulated here. Figures 4.4 and 4.5 show system responses for these two scenarios. Same behavior can be observed in these two scenarios where induction generator’s voltage drop recovery is better with lower WECS ratings and hence lower rotor speed deviation.

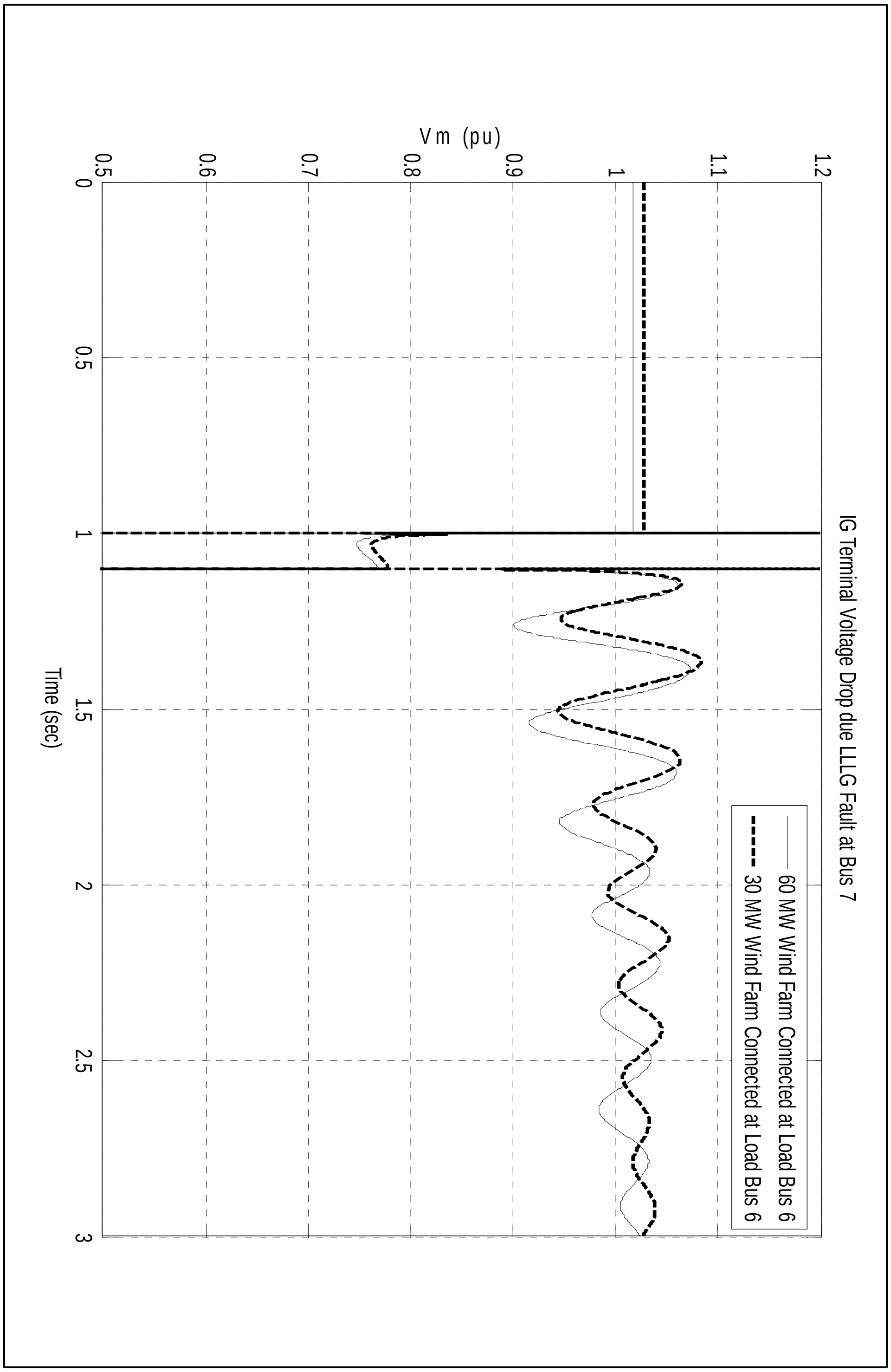

Figure 4.4: IG Terminal Voltage Drop due to LLLG Fault at Bus 7 without STATCOM and PSS

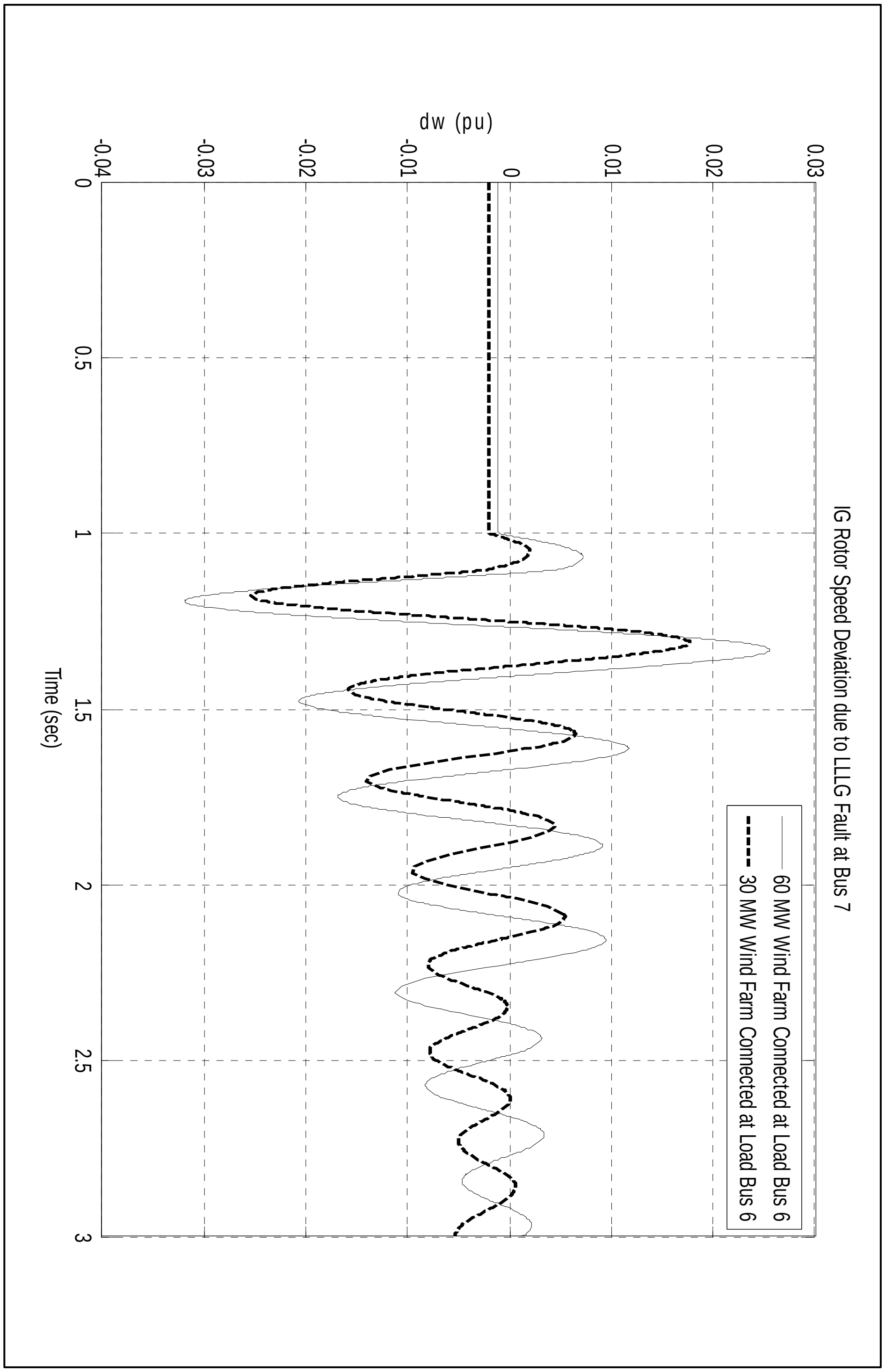

Figure 4.5: IG Rotor Speed Deviation due to LLLG Fault at Bus 7 without STATCOM and PSS

4.5 Summary:

From the results obtained in this chapter, it can be concluded that induction generator terminal voltage drop and therefore its rotor speed deviation are influenced by the rating of wind farm. It has been observed that with higher penetration levels of WECS, more sever terminal voltage drops and rotor speed deviations the induction generator will exhibit. The table below shows a summary of performance indices for the system calculated for each scenario.

Table 4.5: Performance Indices for the System under Different Operating Scenarios of the Base Case

	PI, System Base Case
Operating Scenario 1: **30MW WF at Bus 5**	3.1373
Operating Scenario 2: **60MW WF at Bus 5**	3.1496
Operating Scenario 3: **30MW WF at Bus 6**	2.4603
Operating Scenario 4: **60MW WF at Bus 6**	3.5705

Next chapter will examine the performance of the system after designing STATCOM controllers. It will evaluate the impacts on the voltage drop at the terminals of the induction machine, and rotor speed deviations after tuning STATCOM controllers. Moreover, it will focus on the improvements done on the synchronous machines after tuning PSS's when they are added to synchronous machine.

CHAPTER 5

OPTIMIZATION RESULTS: STATCOM AND PSS PARAMETERS TUNNING USING GENETIC ALGORITHM

5.1 Introduction

In this chapter, STATCOM is installed at the terminals of the wind farm for terminal voltage recovery enhancement. Moreover, PSS's are applied to the excitation system of the synchronous machines. STATCOM internal AC and DC voltage controllers' parameters as well as PSS's parameters are tuned up in order to enhance the stability performance of the system. Since this problem is non-linear problem, optimization algorithm is needed for optimum design of controllers' parameters. In this thesis Genetic Algorithm is used.

5.2 STATCOM Controller Design

STATCOM controllers to be designed are the AC and DC voltage controllers that will control the magnitude and phase of the PWM based switching circuit. This will in turn optimize reactive power injection or absorption into or from the system which will result in better terminal voltage control.

STATCOM rating, when used in voltage regulation applications, is recommended to be 50% of WF ratings in order to guarantee a successful terminal voltage recovery [75]. It is, however, found in some other works varying in the range of 50 – 100 % of WF rating [76]. In this thesis, STATCOM rating of 50% of the WF rating is considered.

STATCOM control parameters to be optimized are the proportional gain and integral time constant for the AC and DC voltage controllers. Genetic Algorithm technique presented in chapter 3 will be used to solve this non-linear problem. The parameters will be optimized for one operating scenario. Same parameters design will be validated for proper control for different operating scenarios.

The parameters will be designed for the operating scenario where 30 MW wind farm is installed at load bus 5. The design will be validated for three different scenarios that were simulated in the previous chapter. They are:

1. 60 MW WF connected at load bus 5.
2. 30 MW WF connected at load bus 6.
3. 60 MW WF connected at load bus 6.

5.3 STATCOM Optimization Approach

Genetic Algorithm is used to tune up the control parameters achieving the following objective:

$F(x) = Min\ (PI_{sys}),$

Subject to the following conditions:

$$K_{p,ac}^{min} < K_{p,ac} < K_{p,ac}^{max} \tag{5.1}$$

$$K_{i,ac}^{min} < K_{i,ac} < K_{i,ac}^{max} \tag{5.2}$$

$$K_{p,dc}^{min} < K_{p,dc} < K_{p,dc}^{max} \tag{5.3}$$

$$K_{i,dc}^{min} < K_{i,dc} < K_{i,dc}^{max} \tag{5.4}$$

Where,

PI_{sys}	performance index for multi-machine system
AC, DC	denotes STATCOM AC or DC voltage controller
K_p	controller proportional gain
K_i	controller integral time constant
min, max	boundaries of an optimum solution

The constraints are arbitrarily chosen to give wide solution range. The ranges are from -100 to 100 for the internal STATCOM controllers. The fitness function that is used to assess the quality of a gene or solution is the multi-machine model including wind farm and STATCOM controllers. In every iteration, a set of control parameters within the ranges specified above are passed to the model, evaluated, and the fitness function value is returned to the algorithm for assessment. The number of generations is the criteria at which when exceeded the algorithm will be stopped. It is chosen to be 50. Population in each generation is 1500. The crossover and mutation factors are 0.8 and 0.2, respectively.

The optimization algorithm is simulated using the 30 MW wind farm located at load bus 5 model and has resulted in the following STATCOM design parameters.

Table 5.1: STATCOM Controller Tuned Parameters

	Parameter	**Value**
STATCOM, AC Controller	Kp,ac	10.0351
	Ki,ac	0.00211
STATCOM, DC Controller	Kp,dc	0.1590
	Ki,dc	0.2333

5.4 STATCOM Optimized Controllers Simulation Results

5.4.1 30 MW Wind Farm at Load Bus 5

Time-domain simulations are carried out given the design parameters in table 5.1. The performance of the system is now re-assessed with STATCOM being shunted with wind farm of 30 MW at load bus 5. Same disturbance that was applied to the base case without STATCOM is applied in this scenario. Figures 5.1 show induction generator terminal voltage drop. Since voltage drop at the terminals of the induction machine is now minimized with the use of optimized STATCOM controllers, the difference between electromagnetic and mechanical torques is now reduced. Therefore, fluctuations in the rotor speed are minimized as well as can be observed in figure 5.2.

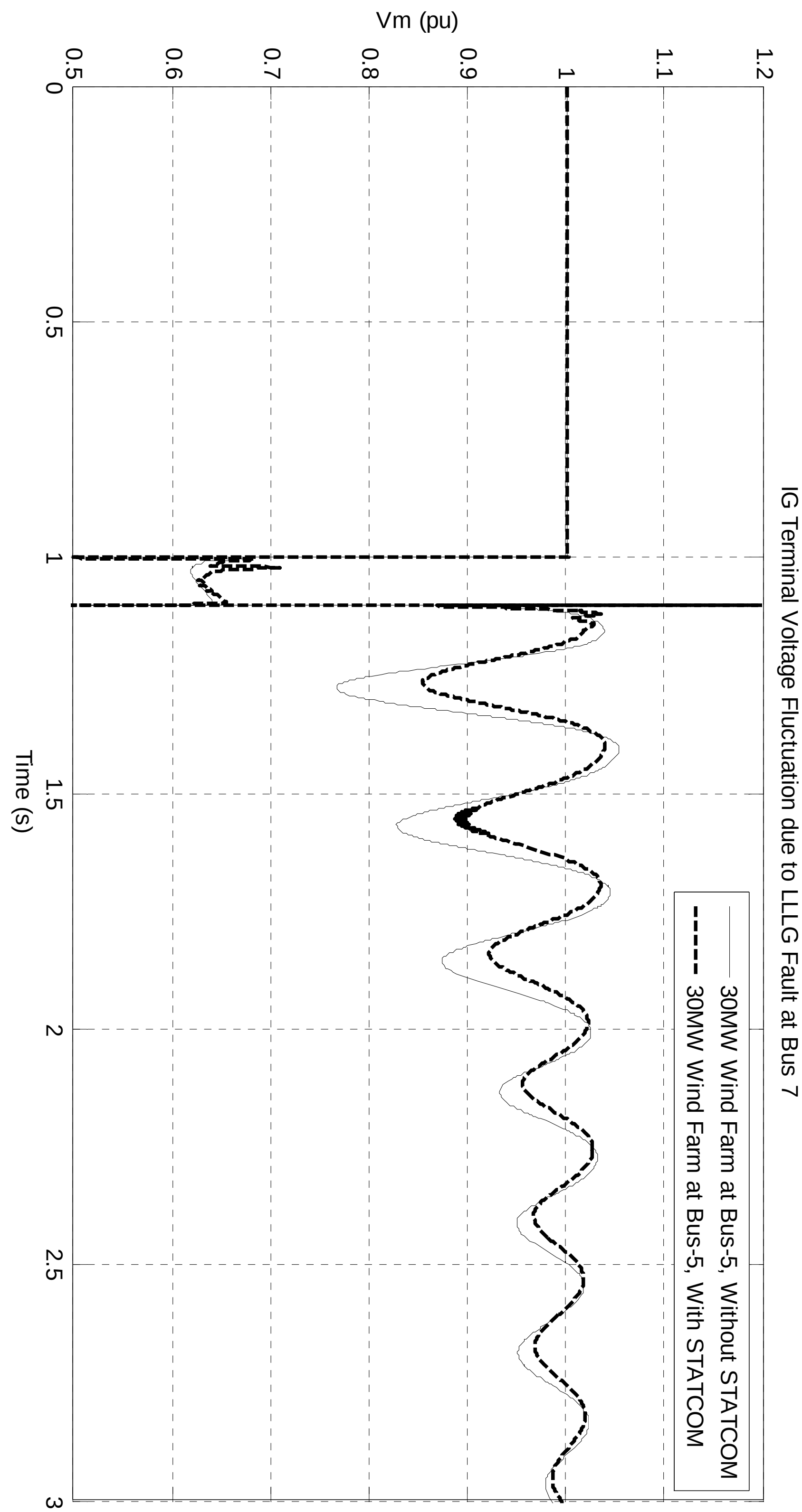

Figure 5.1: IG Terminal Voltage Fluctuations with Optimized STATCOM Controller

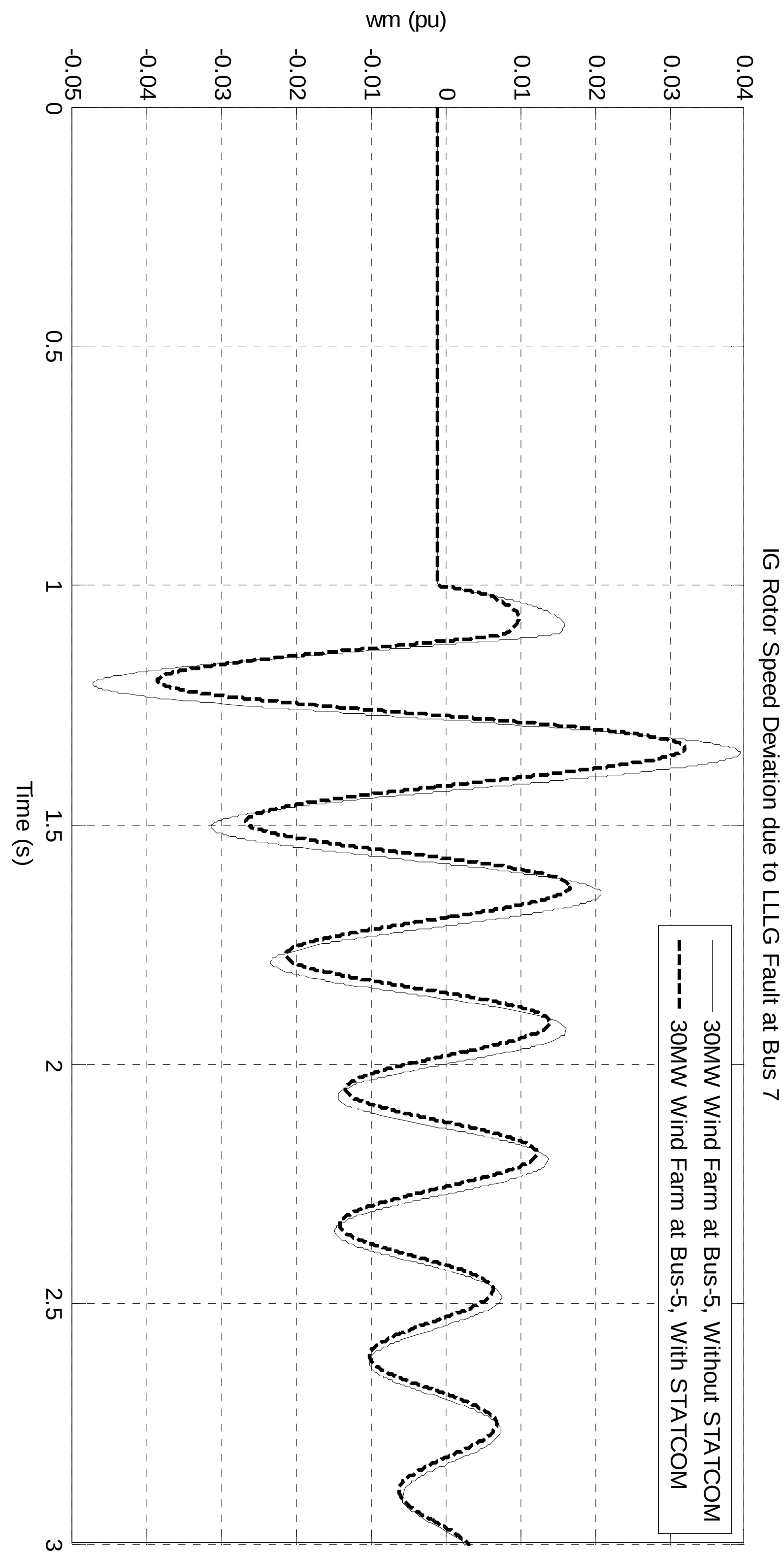

Figure 5.2: IG Rotor Speed Deviation with Optimized STATCOM Controller

Synchronous machines stability is observed after installing STATCOM at wind farm. Figures 5.3 and 5.4 show rotor angle deviations with respect to the slack bus for both synchronous generators 2 and 3 of the nine bus system.

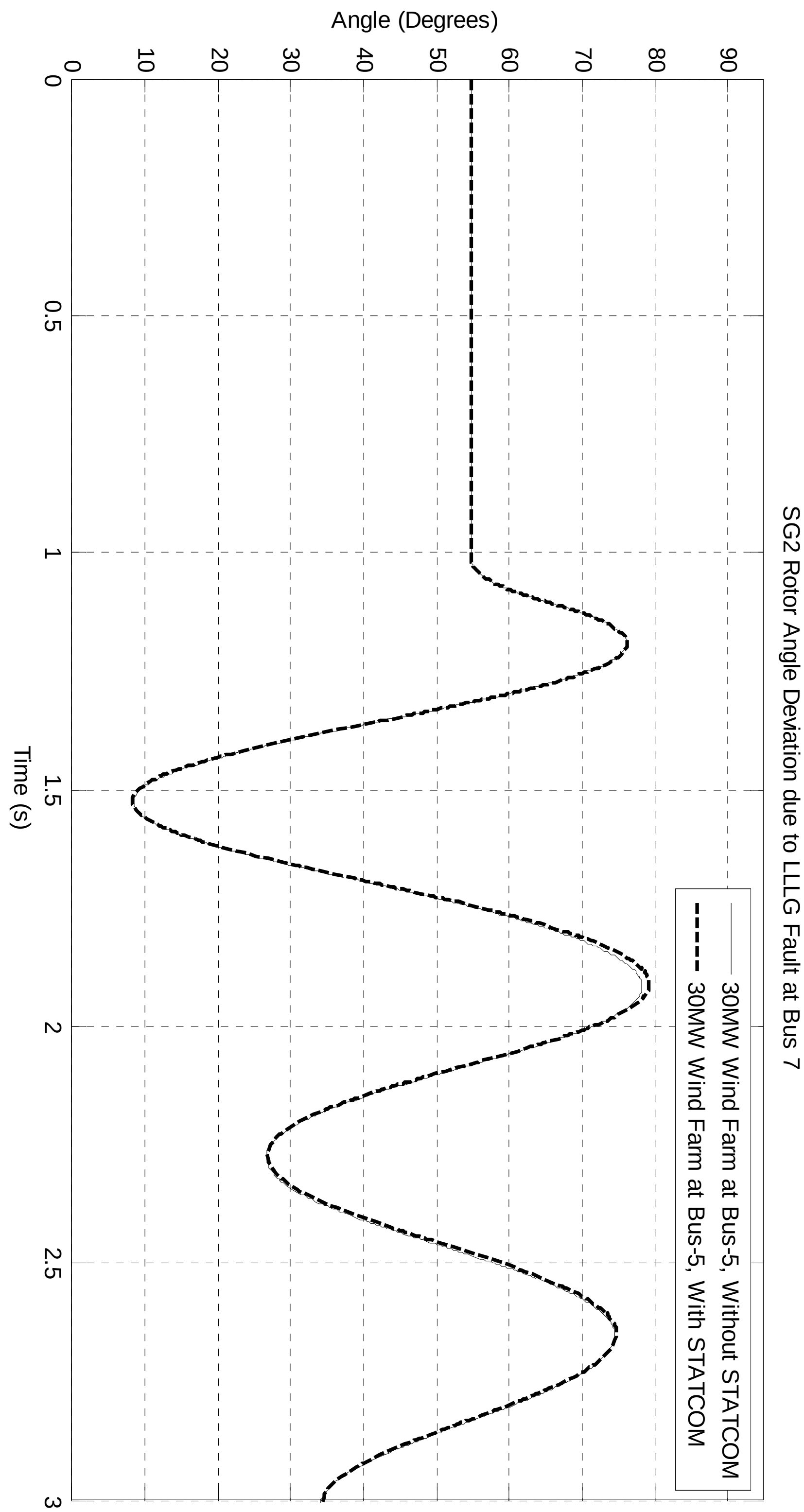

Figure 5.3: SG-2 Rotor Angle Deviation after Optimizing STATCOM Controller

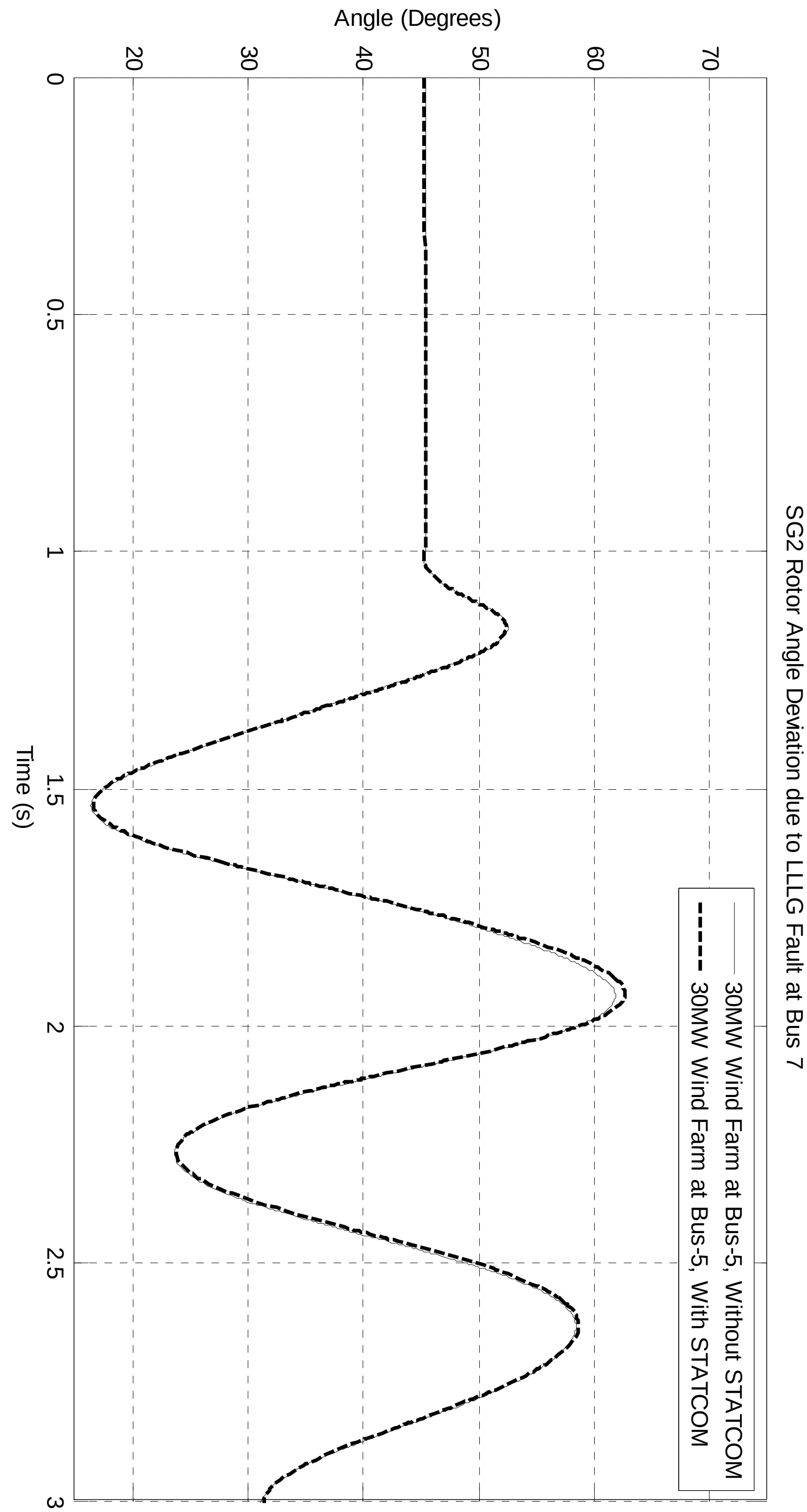

Figure 5.4: SG-3 Rotor Angle Deviation after Optimizing STATCOM Controller

5.4.2 60 MW Wind Farm at Load Bus 5

Time domain simulations are carried out on the multi-machine system with increased rating wind farm installed at load bus 5. The figures from 5.5 to 5.6 show that the optimized STATCOM control parameters are still enhancing terminal voltage recovery and induction generator’s rotor speed deviation.

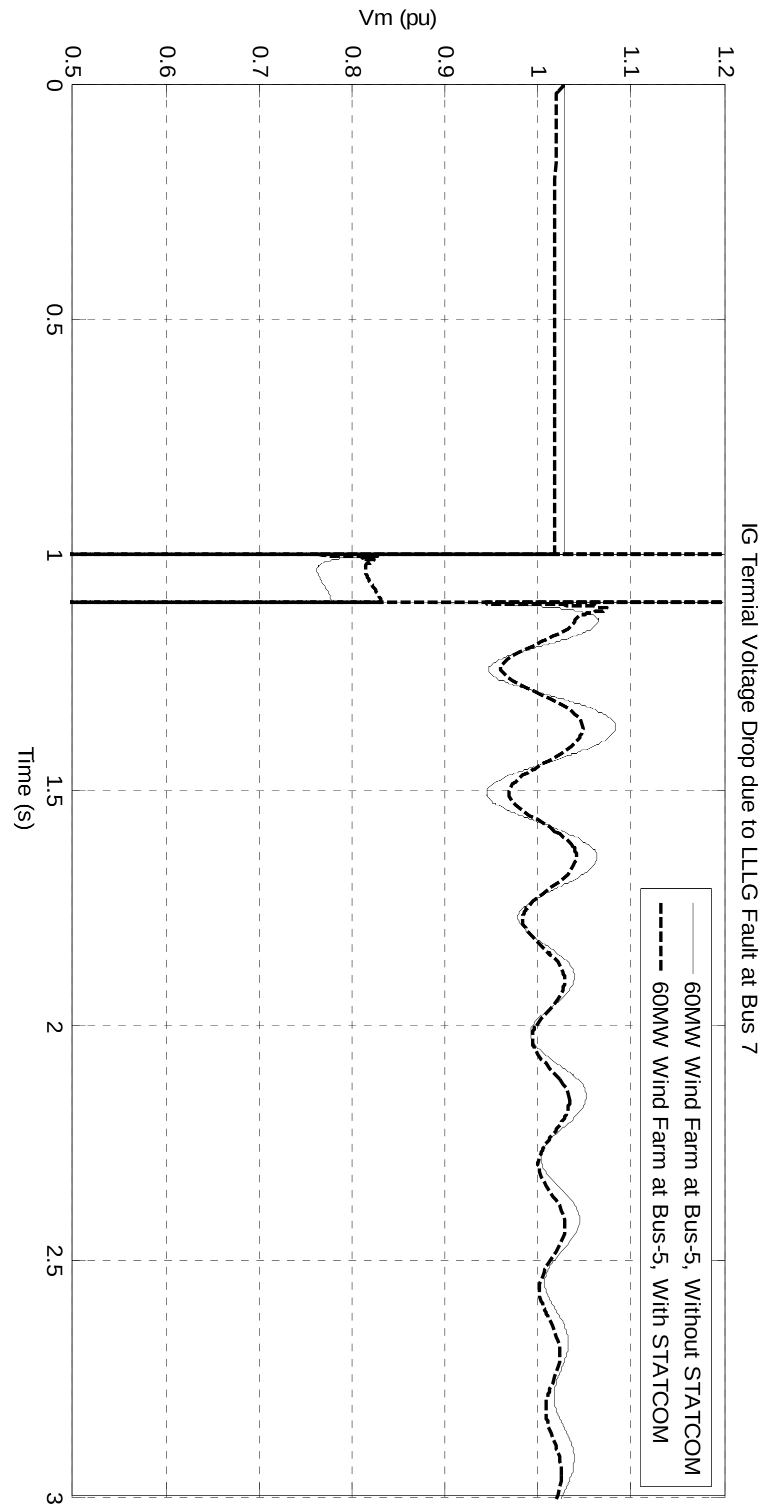

Figure 5.5: IG Terminal Voltage Fluctuations with Optimized STATCOM Controller at 60 MW Wind Farm at Load Bus 5

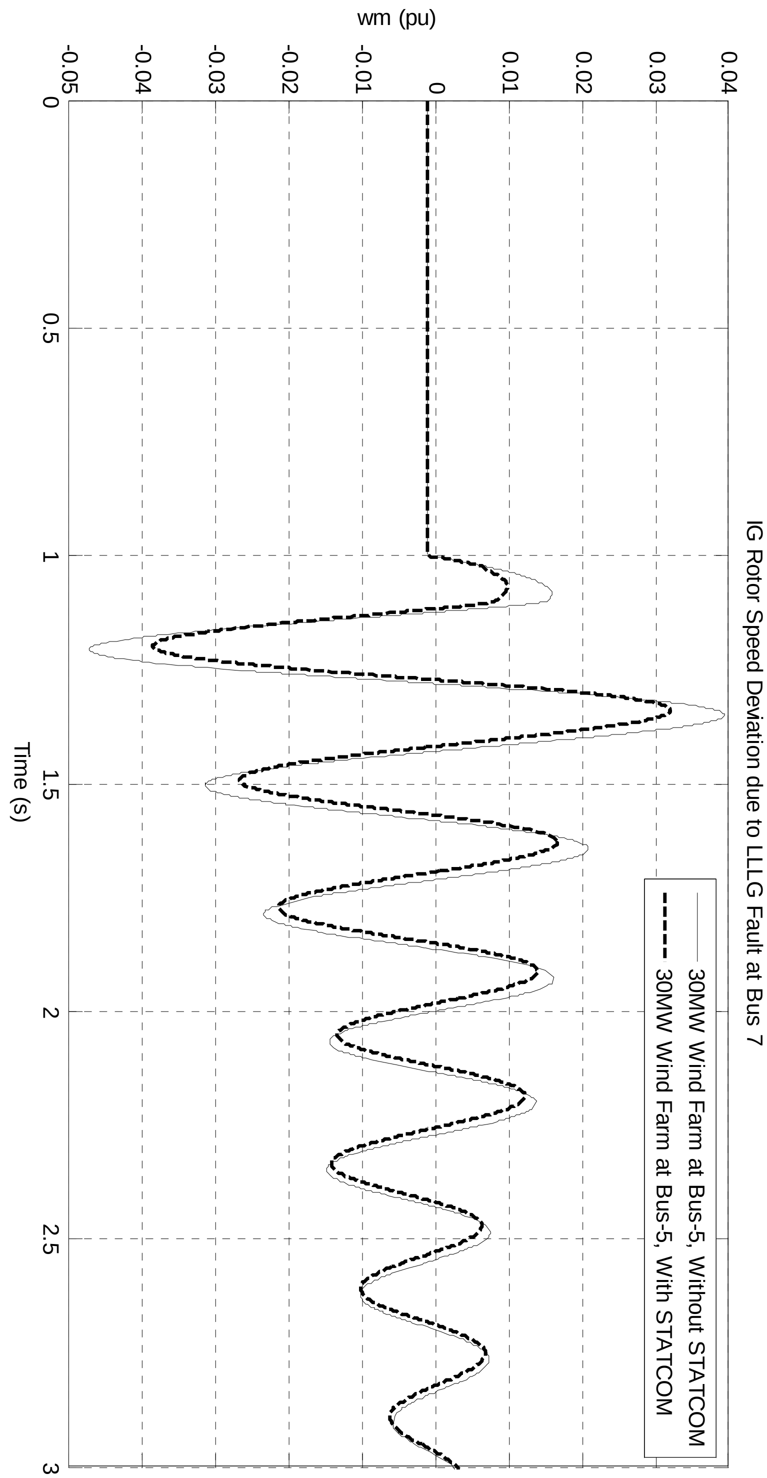

Figure 5.6: IG Rotor Speed Deviations with Optimized STATCOM Controller at 60 MW Wind Farm at Load Bus 5

Rotor angle deviations for synchronous generators 2 and 3 are observed in this case with a slight improvement as shown in figures 5.7 and 5.8, respectively.

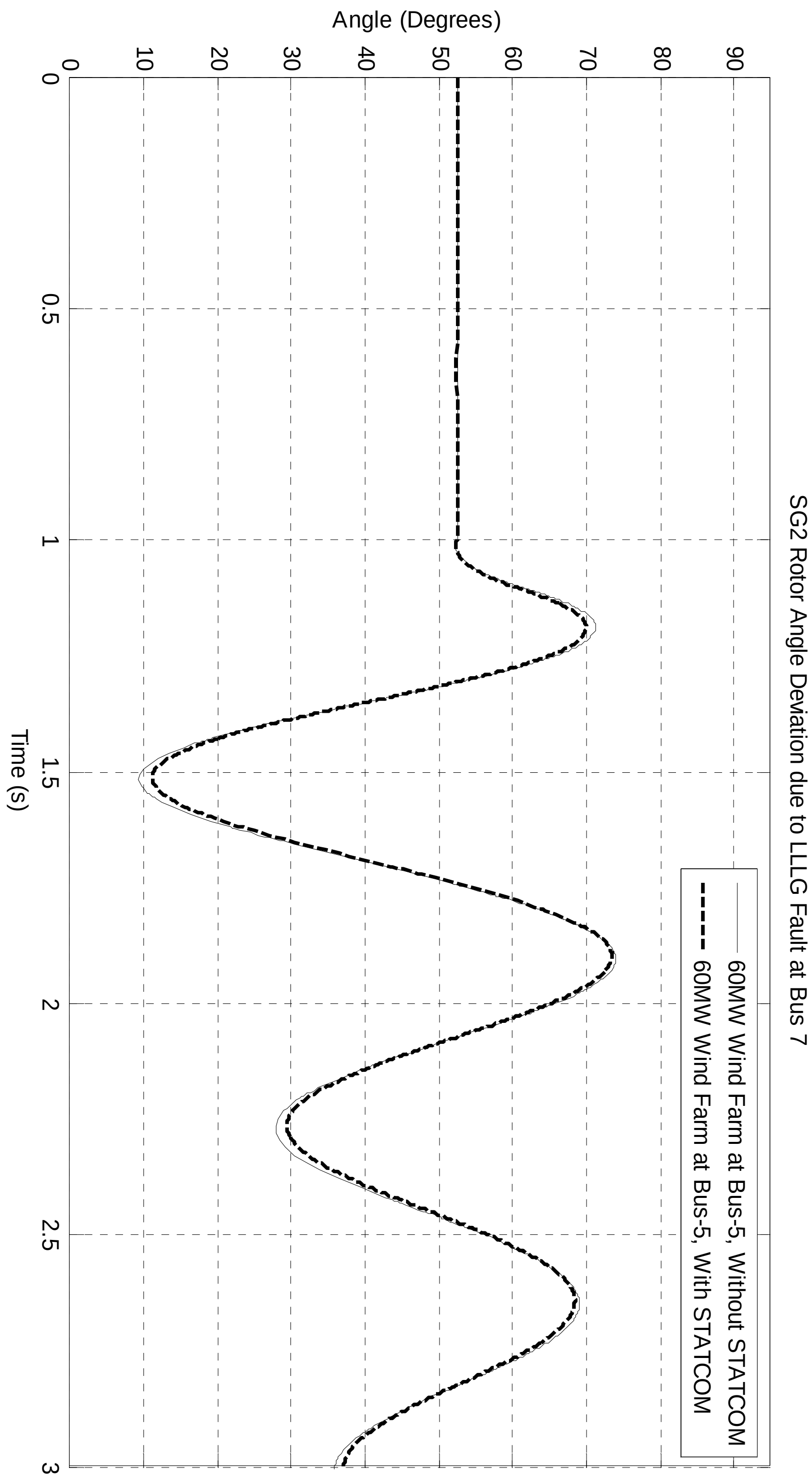

Figure 5.7: SG-2 Rotor Angle Deviation after Optimizing STATCOM Controller at 60 MW Wind Farm at Load Bus 5

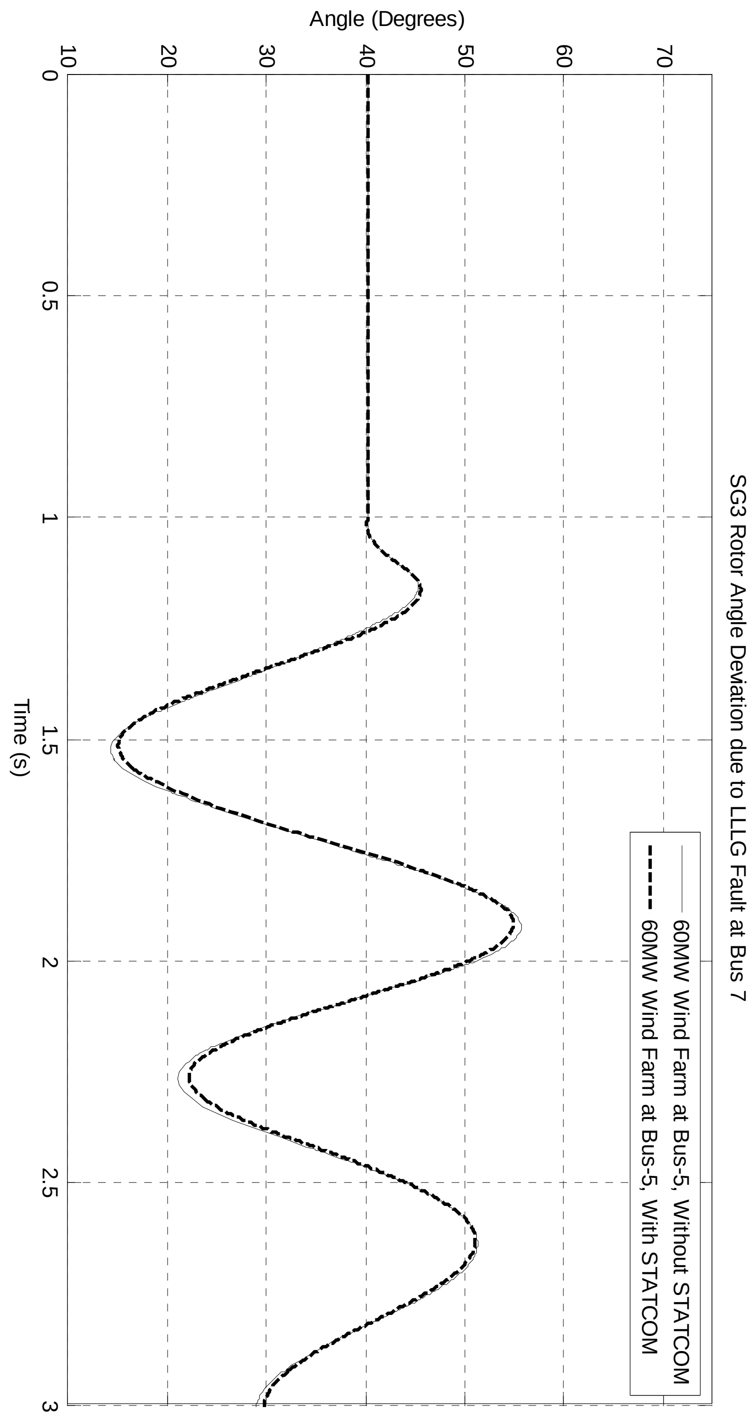

Figure 5.8: SG-3 Rotor Angle Deviation after Optimizing STATCOM Controller at 60 MW Wind Farm at Load Bus 5

5.4.3 30 MW Wind Farm at Load Bus 6

Wind farm with STATCOM based voltage control is now simulated at a different load bus in order to examine the impact of wind farm location on the stability of electrical power system. Wind farm is now connected at load bus 6. The rating of the wind farm is 30 MW and STATCOM optimized control parameters are re0used here in the time domain simulations. The results show a significant improvement in the terminal voltage recovery as well as induction generators' rotor speed deviation.

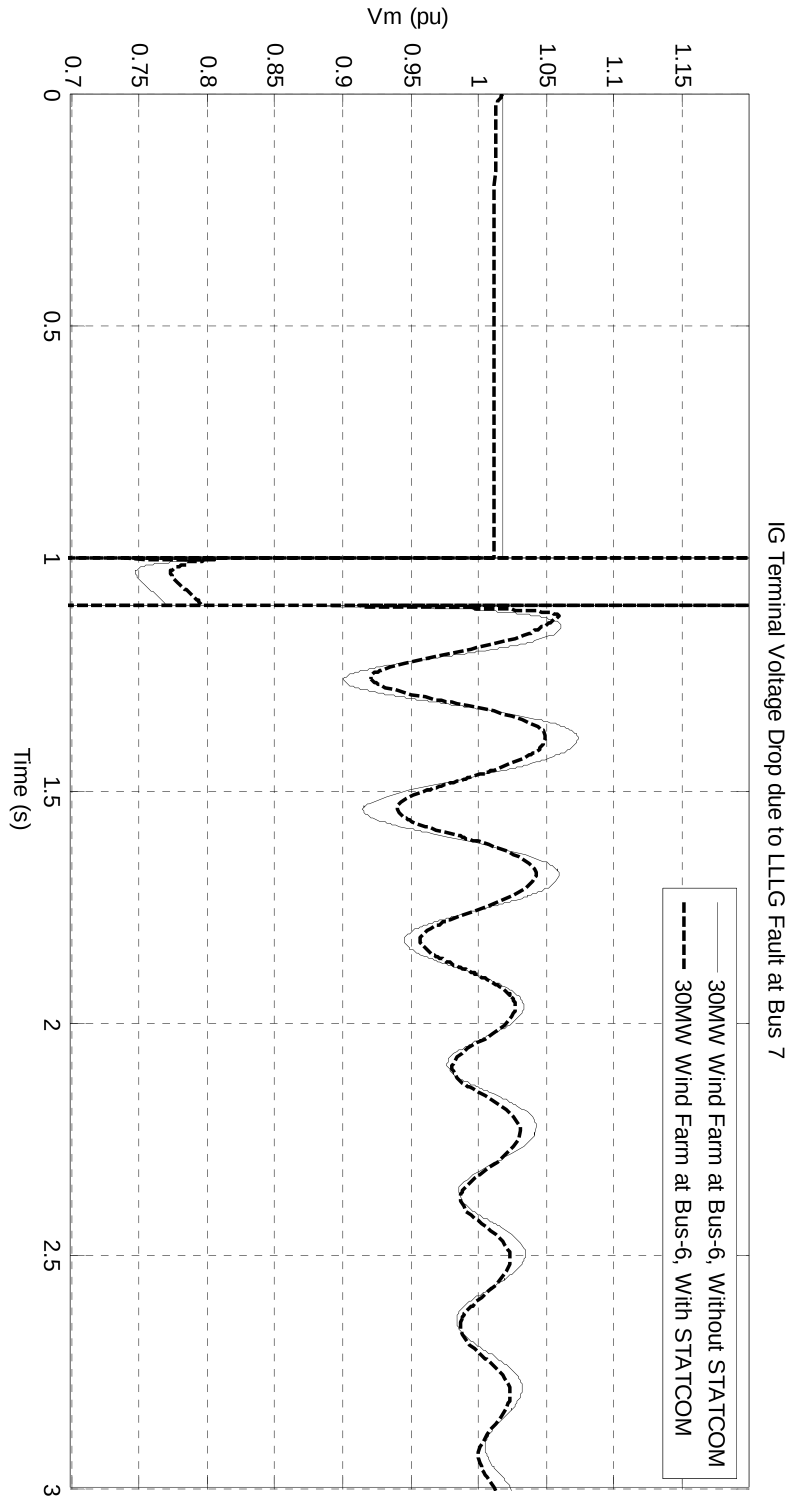

Figure 5.9: IG Terminal Voltage Fluctuations with Optimized STATCOM Controller at 30 MW Wind Farm at Load Bus 6

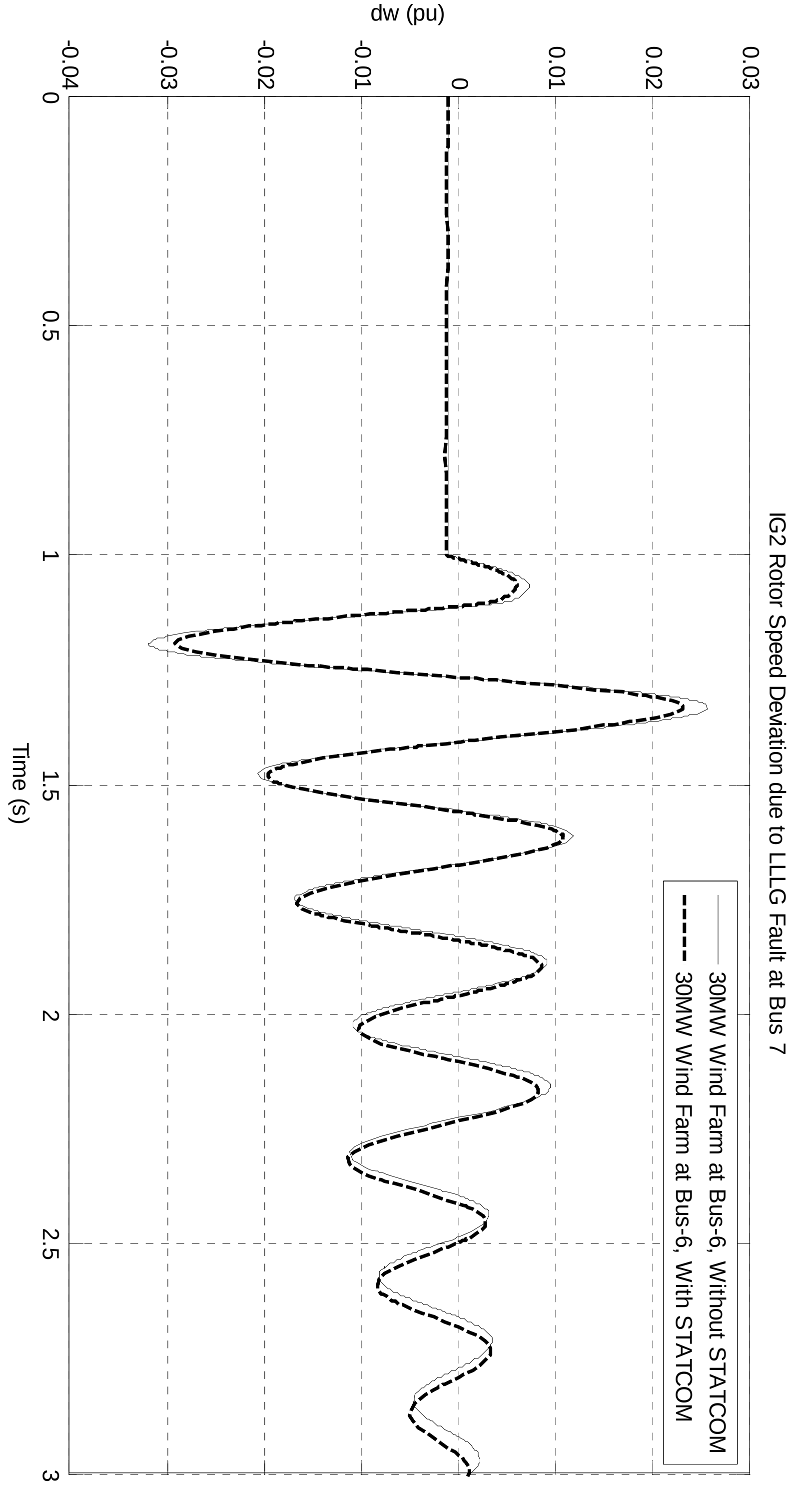

Figure 5.10: IG Rotor Speed Deviations with Optimized STATCOM Controller at 30 MW Wind Farm at Load Bus 6

In contrast to terminal voltage recovery and rotor speed deviation, synchronous generator’s rotor angles maintained almost same performance without STATCOM.

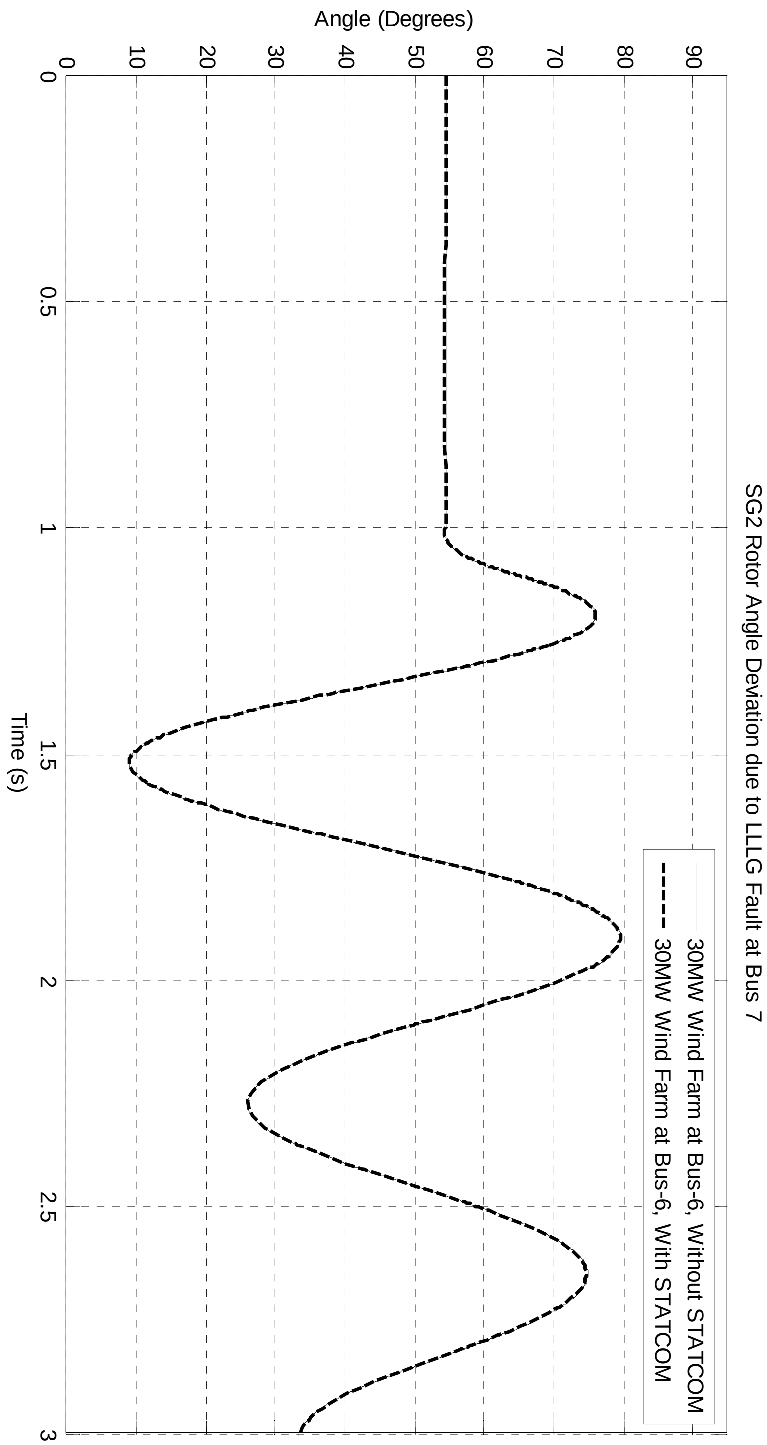

Figure 5.11: SG-2 Rotor Angle Deviation after Optimizing STATCOM Controller at 30 MW Wind Farm at Load Bus 6

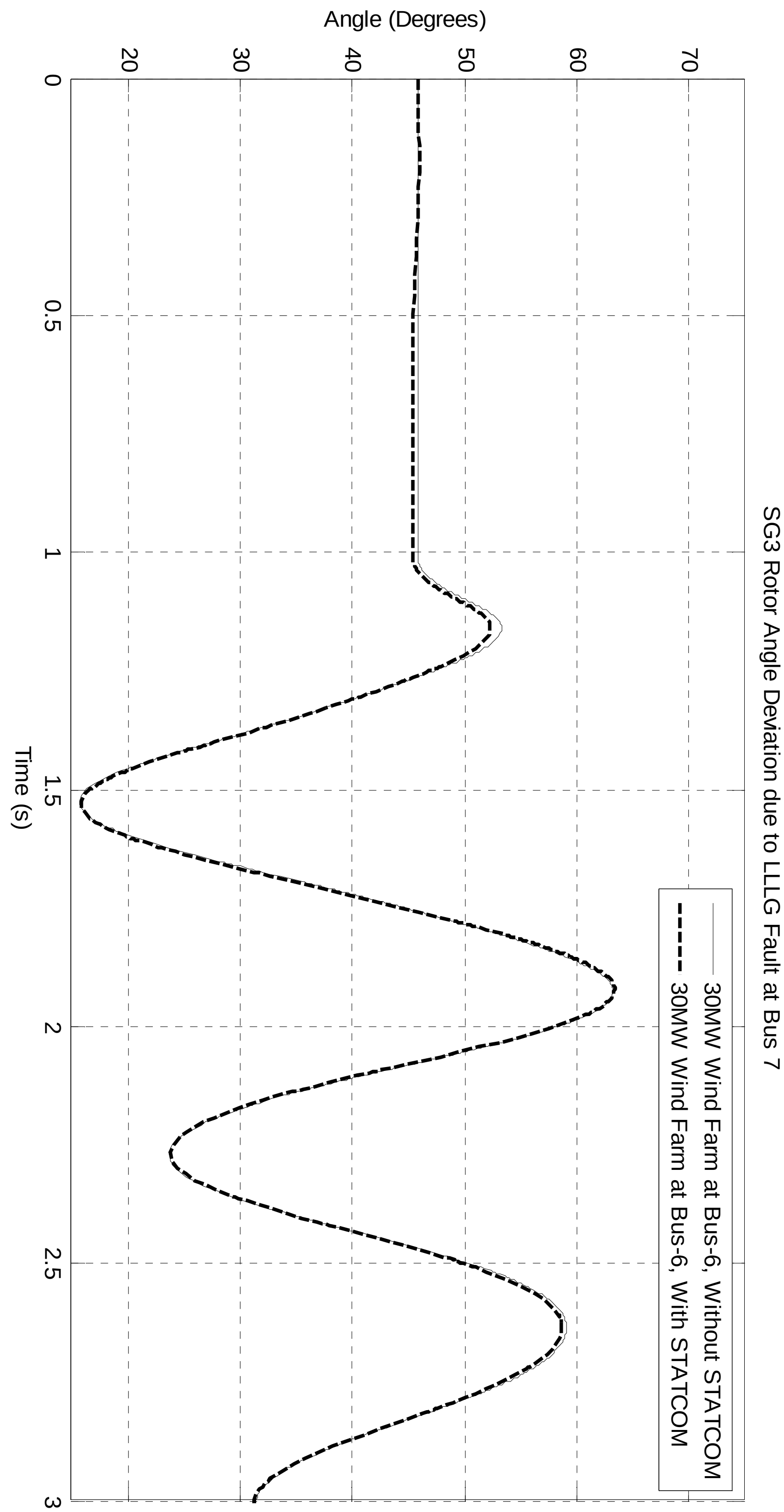

Figure 5.12: SG-3 Rotor Angle Deviation after Optimizing STATCOM Controller at 30 MW Wind Farm at Load Bus 6

5.4.4 60 MW Wind Farm at Load Bus 6

With 60 MW wind farm installed at the same load bus, same behavior is observed for terminal voltage recover, rotor speed deviations, and synchronous generators' rotor angles.

From the results shown in this section, it can be concluded that optimized STATCOM controllers parameters have contributed to the enhancement of induction generators stability. They, however, slightly contributed to the enhancement of the system. Hence, next sections will deal with tuning PSS's of the excitation system used with synchronous generators for system stability enhancement. Re-optimizing STATCOM controllers' parameters will be performed as well.

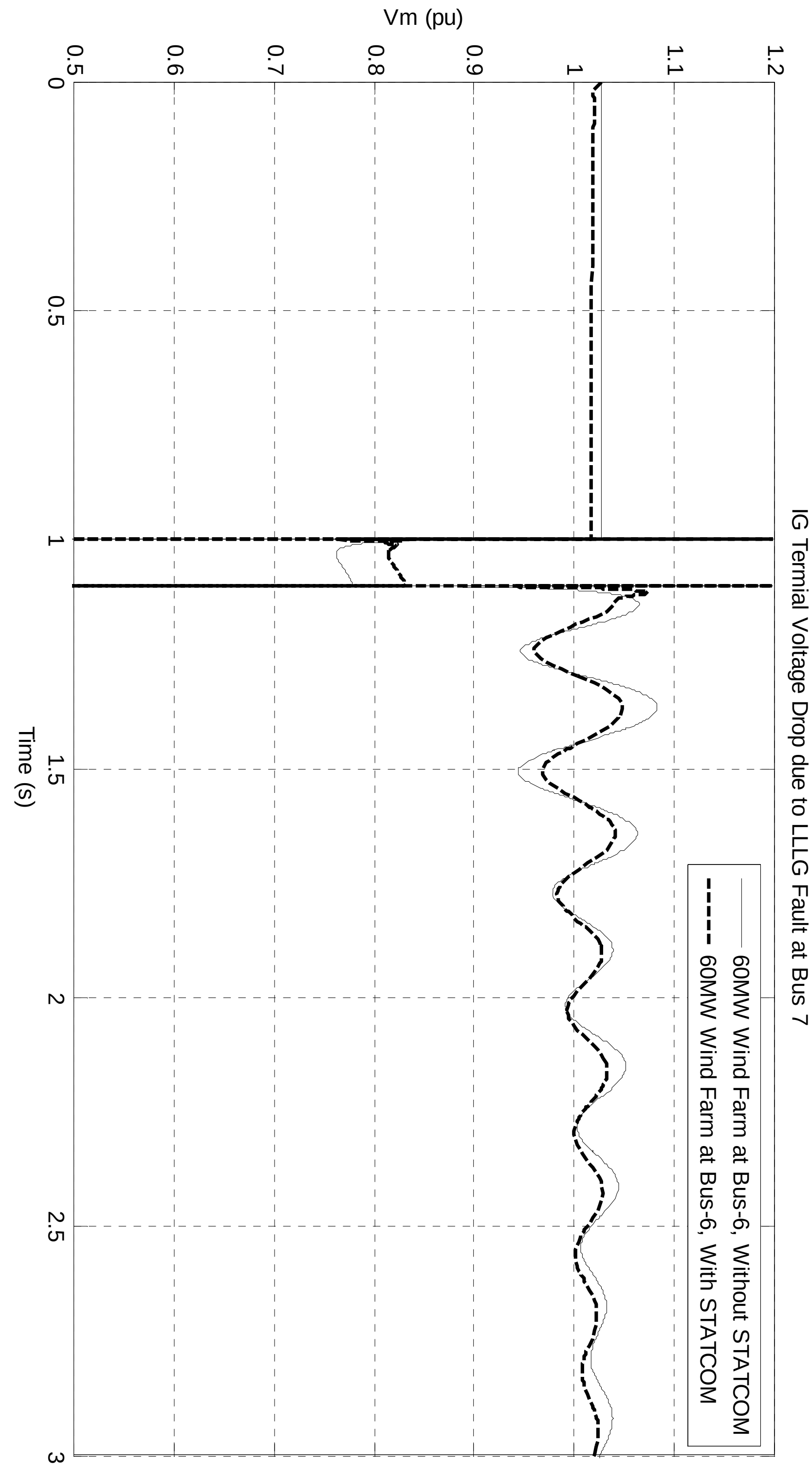

Figure 5.13: IG Terminal Voltage Fluctuations with Optimized STATCOM Controller at 60 MW Wind Farm at Load Bus 6

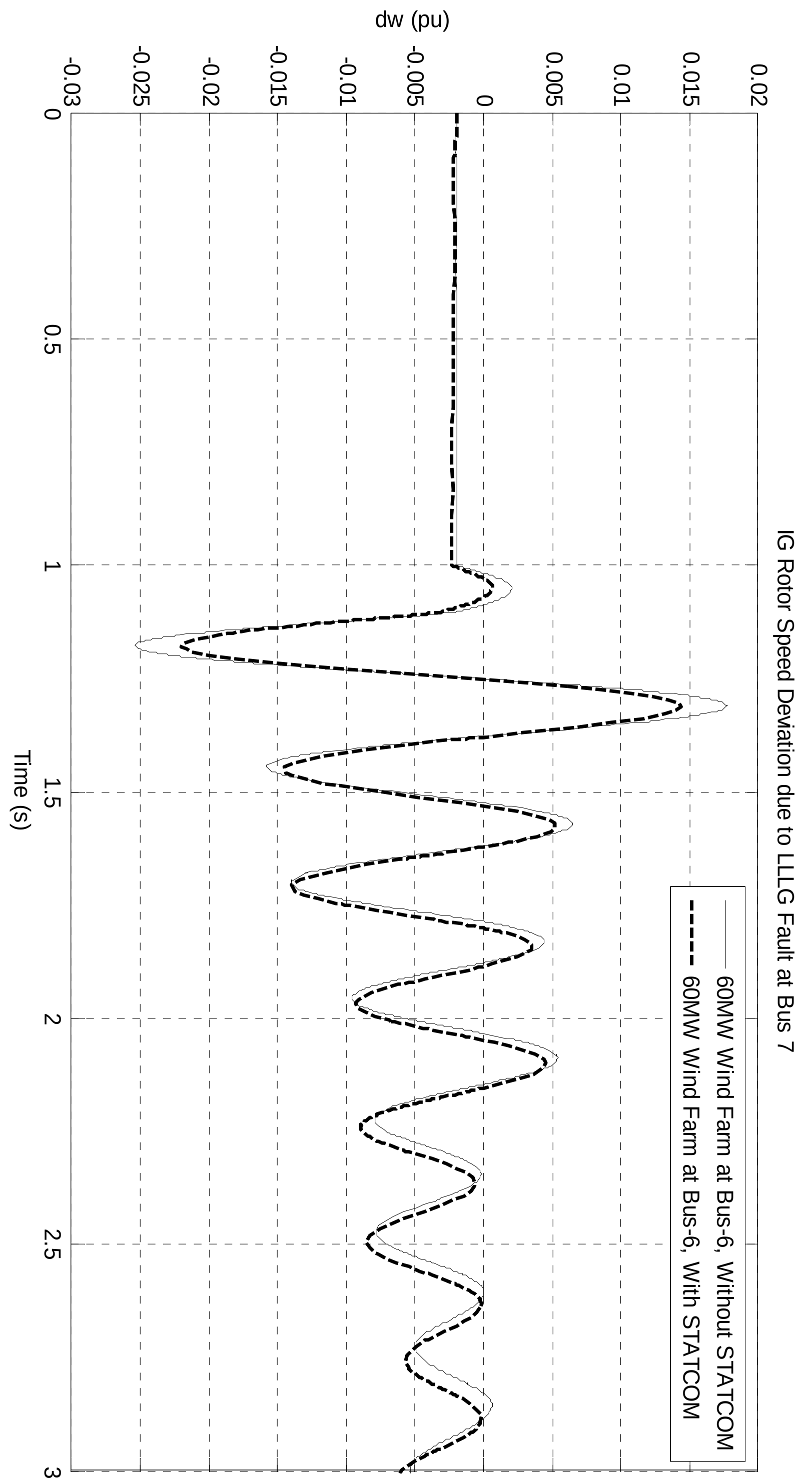

Figure 5.14: IG Rotor Speed Deviations with Optimized STATCOM Controller at 60 MW Wind Farm at Load Bus 6

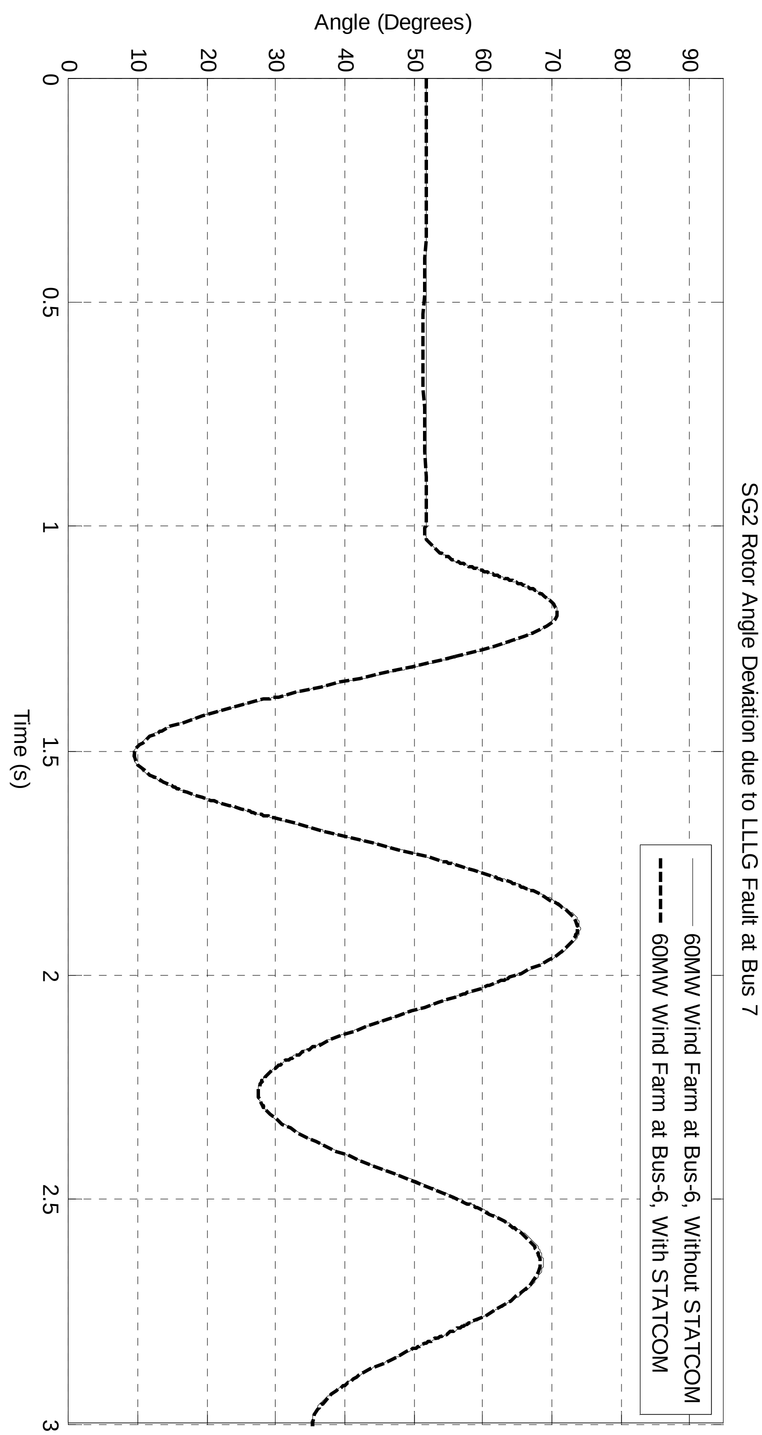

Figure 5.15: SG-2 Rotor Angle Deviation after Optimizing STATCOM Controller at 60 MW Wind Farm at Load Bus 6

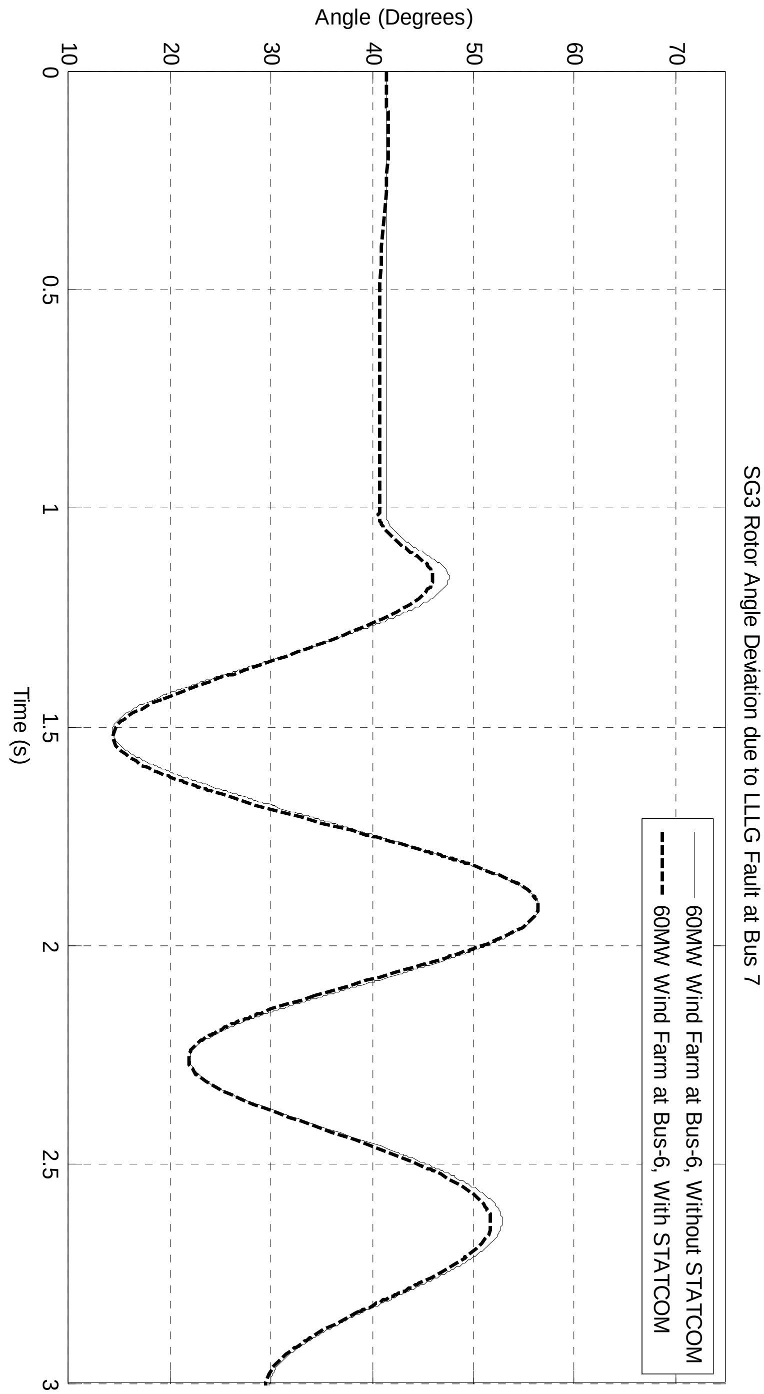

Figure 5.16: SG-3 Rotor Angle Deviation after Optimizing STATCOM Controller at 60 MW Wind Farm at Load Bus 6

5.5 PSS Design

The use and design of PSS is aimed at damping synchronous generators oscillations. The design involves optimizing the controller gain, phase compensation time constants and signal washout block time constant of PSS. In this thesis, however, only controller's gain, K, and phase compensation blocks' time constants, T1 and T3, will be optimized while the time constants T2 and T4 as well as signal washout block time constant, Tw, will be fixed. They will be 0.05, 0.05 and 5 for both synchronous generators 2 and 3, respectively [59].

5.6 PSS Optimization Approach

Optimization approach used for optimizing STATCOM controllers is used here for optimizing PSS parameters. Furthermore to the constraints applied in optimizing STATCOM controllers, the following constraints are added when optimizing PSSs for synchronous generators 2 and 3:

$$K_{,SG2}^{min} < K_{,SG2} < K_{,SG2}^{max} \tag{5.5}$$

$$T1_{,SG2}^{min} < T1_{,SG2} < T1_{,SG2}^{max} \tag{5.6}$$

$$T3_{,SG2}^{min} < T3_{,SG2} < T3_{,SG2}^{max} \tag{5.7}$$

$$K_{,SG3}^{min} < K_{,SG3} < K_{,SG3}^{max} \tag{5.8}$$

$$T1_{,SG3}^{min} < T1_{,SG3} < T1_{,SG3}^{max} \tag{5.9}$$

$$T3_{,SG3}^{min} < T3_{,SG3} < T3_{,SG3}^{max} \tag{5.10}$$

Where,

K	PSS gain
T1 and T3	PSS phase compensation blocks' time constants
SG2 and SG3	synchronous generators 2 and 3
min, max	boundaries of an optimum solution

The optimization of PSS's gains will be constrained in the range's minimum and maximum values of 1 to 20. On the other hand, optimizing phase compensation time constants will be in the range from 0.01 to 5. The minimum and maximum constraint's ranges for optimizing STATCOM controllers are kept the same as earlier.

5.7 PSS Optimized Controllers Simulation Results

The optimization process to obtain optimum tuning parameters is done for all controllers simultaneously and independently and the variables are passed from the algorithm to the model with the same weight. The tuning process is done on the same model and operation scenario of 30 MW wind farm installed at load bus 5 same what was done while tuning STATCOM controllers only. The tuned parameters are indicated in table 5.3.

Table 5.2: STATCOM and PSS Tuned Parameters for System Stability Enhancement

	Parameter	**Value**
STATCOM, AC Controller	Kp, ac	90.877
	Ki, ac	74.45
STATCOM, DC Controller	Kp, dc	0.1590
	Ki, dc	45.85
SG 2, PSS	K	19.29
	T1	0.0201
	T3	0.344
SG 3, PSS	K	15.51
	T1	0.7879
	T3	0.441

5.8 PSS and STATCOM Optimized Controllers Simulation Results

5.8.1 30 MW Wind Farm at Load Bus 5

Time-domain simulations are now re-performed given the optimized PSS parameters and the new STATCOM controllers' parameters. The previous time-domain simulations for the base cases without STATCOM and PSS, and for the case with STATCOM are included also for comparison purposes. Time-domain simulations for the case of 30 MW wind farm located at bus 5 is simulated and shown in figures 5.17 to 5.20.

Terminal voltage drops at induction generators are kept the same even after tuning PSS and re-tuning the STATCOM controllers. Similarly, induction generator's rotor speed deviation is close to its performance while tuning STATCOM controllers alone.

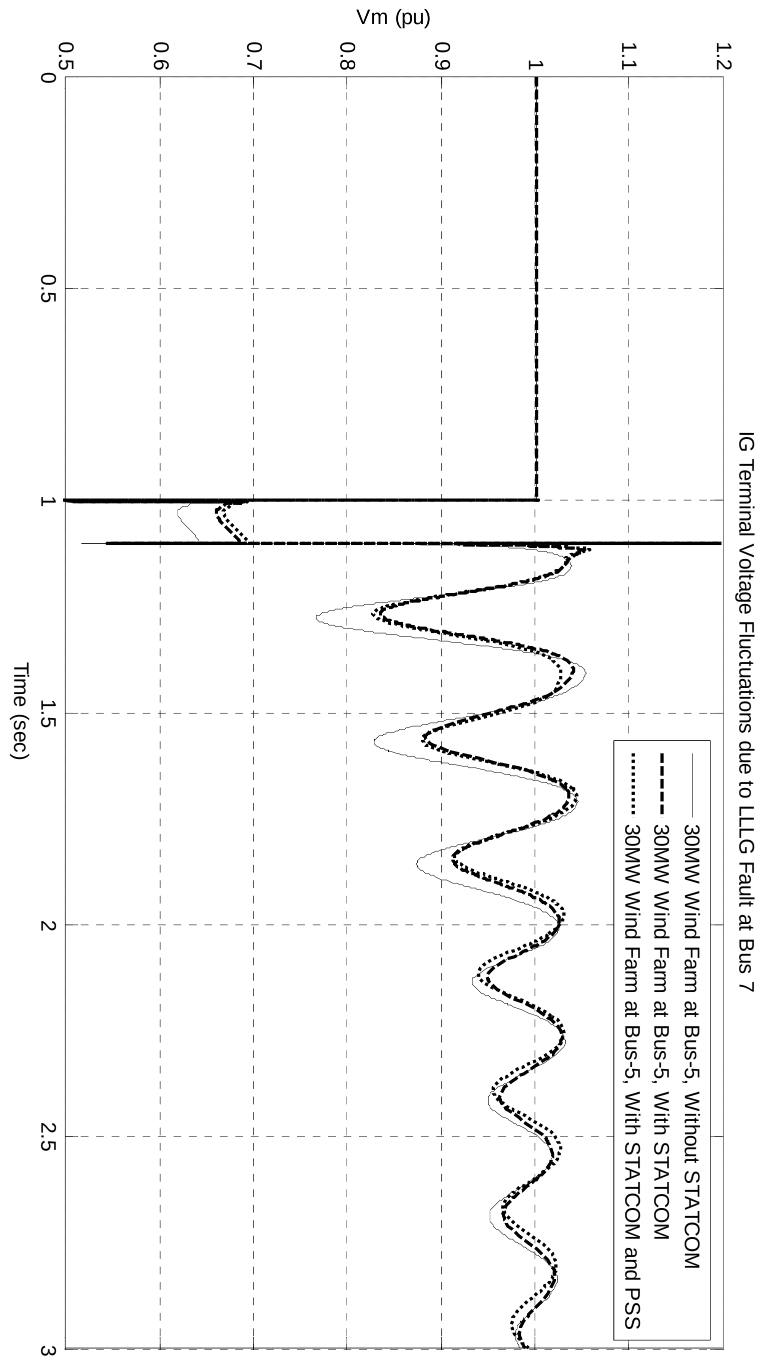

Figure 5.17: IG Terminal Voltage Drop after STATCOM and PSS Parameters Tuning

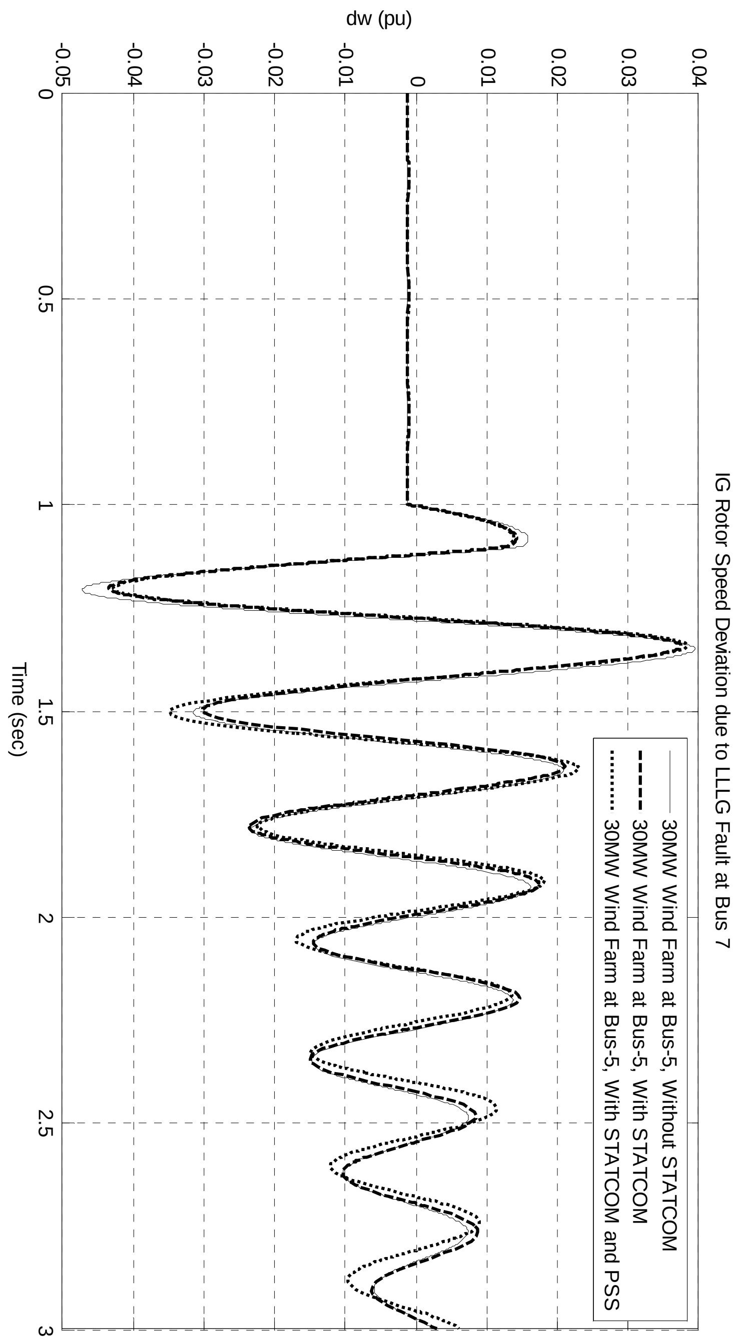

Figure 5.18: IG Rotor Speed Deviation after STATCOM and PSS Parameters Tuning

Tuning PSS parameters has been successfully achieved where the oscillations damping is tangibly achieved. Refer to figures 5.19 and 5.20 where it can be clearly noticed that PSS has a significant impact on the stability of synchronous generators.

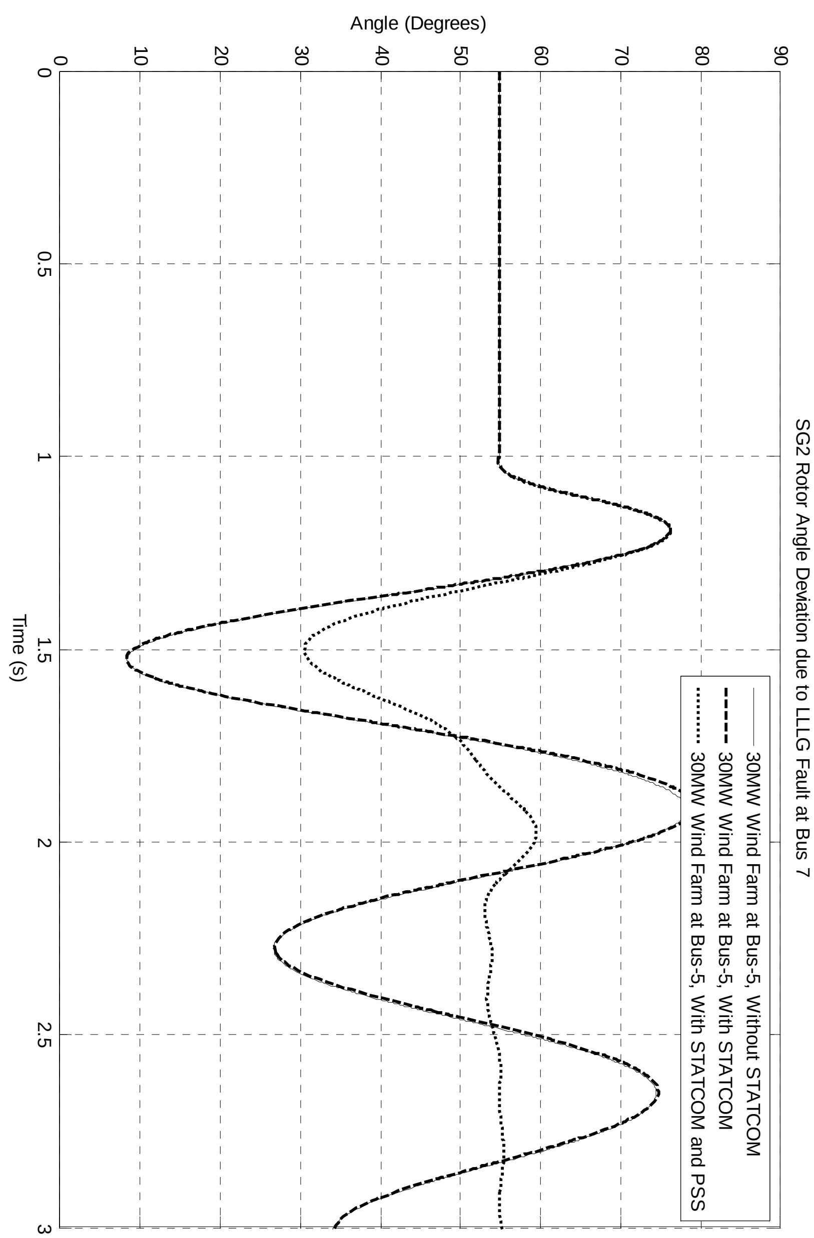

Figure 5.19: SG2 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning

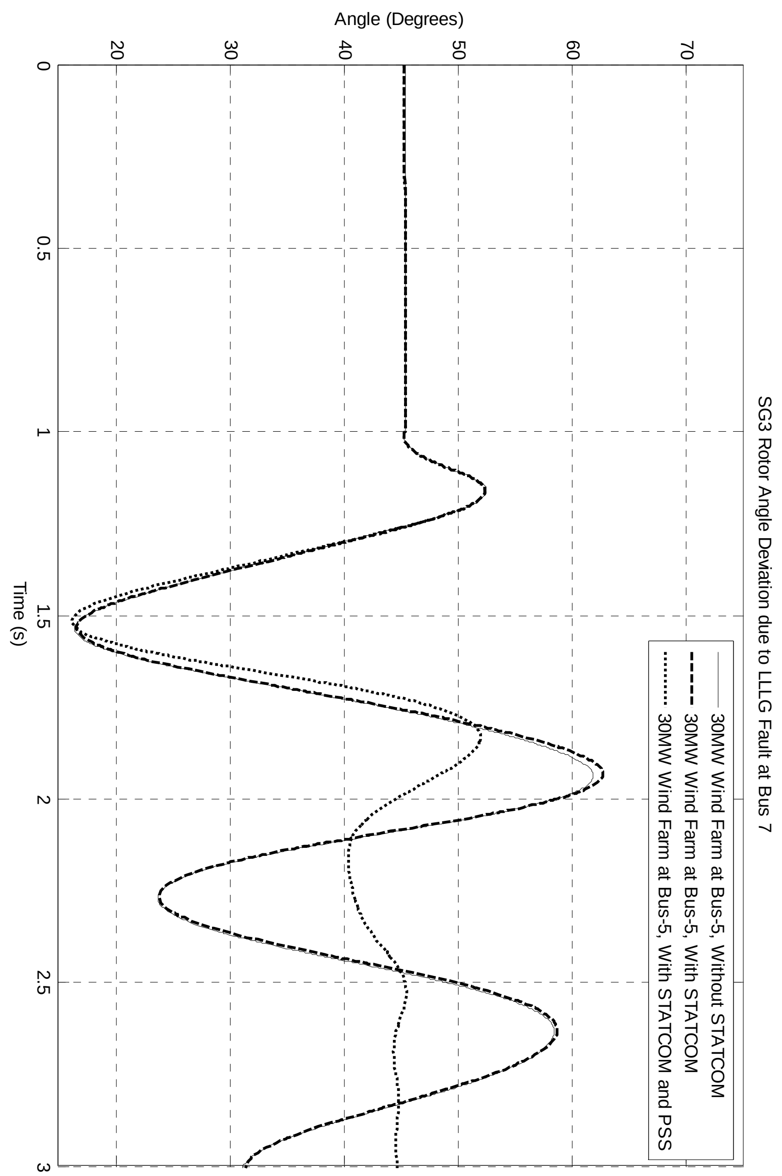

Figure 5.20: SG3 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning

5.8.2 60 MW Wind Farm at Load Bus 5

Re-tuning of STATCOM controllers after adding PSS to the synchronous generators is also achieving a better performance than the case without STATCOM as can be seem from figures 5.21 and 5.22.

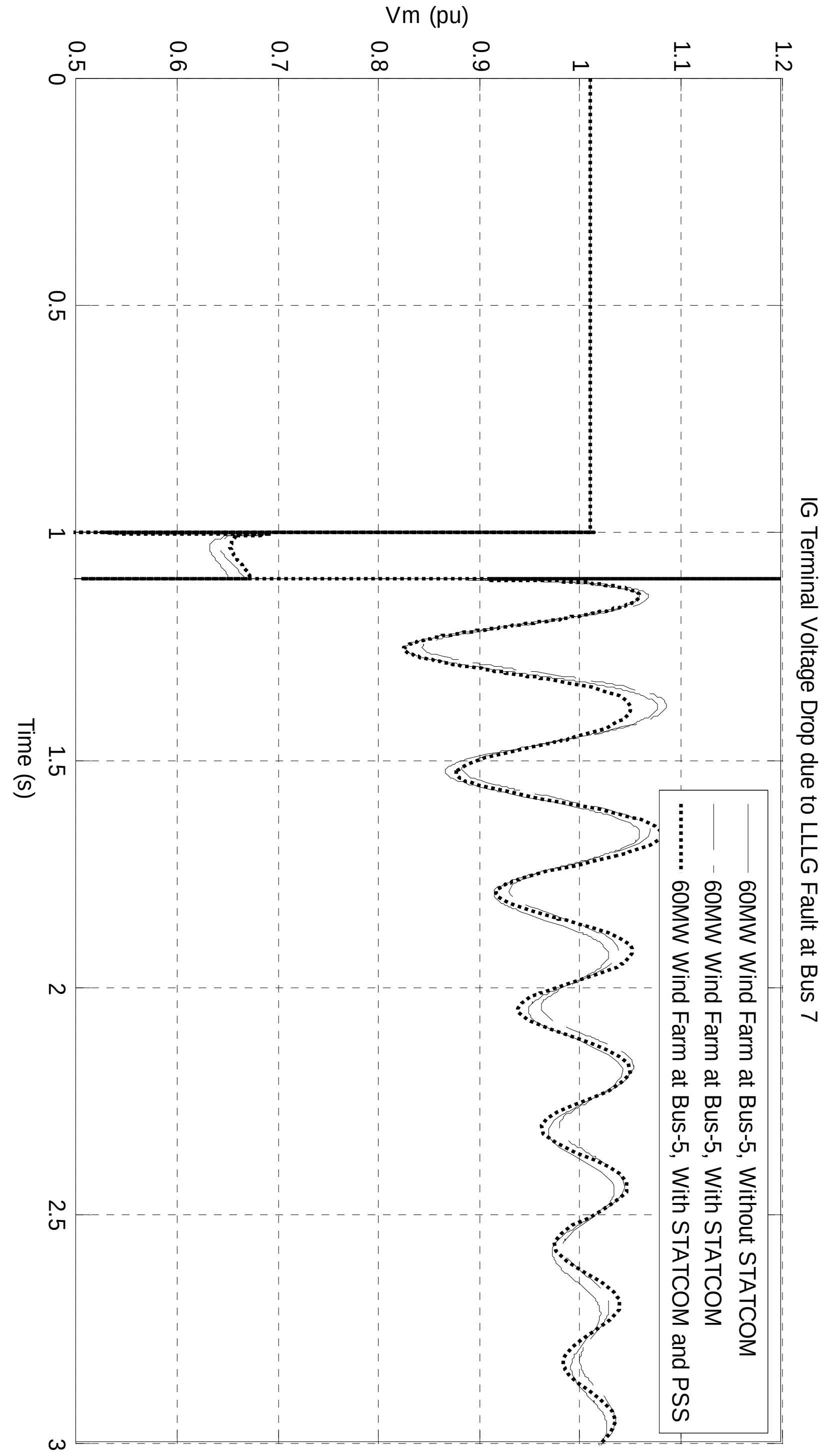

Figure 5.21: IG Terminal Voltage Drop after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 5

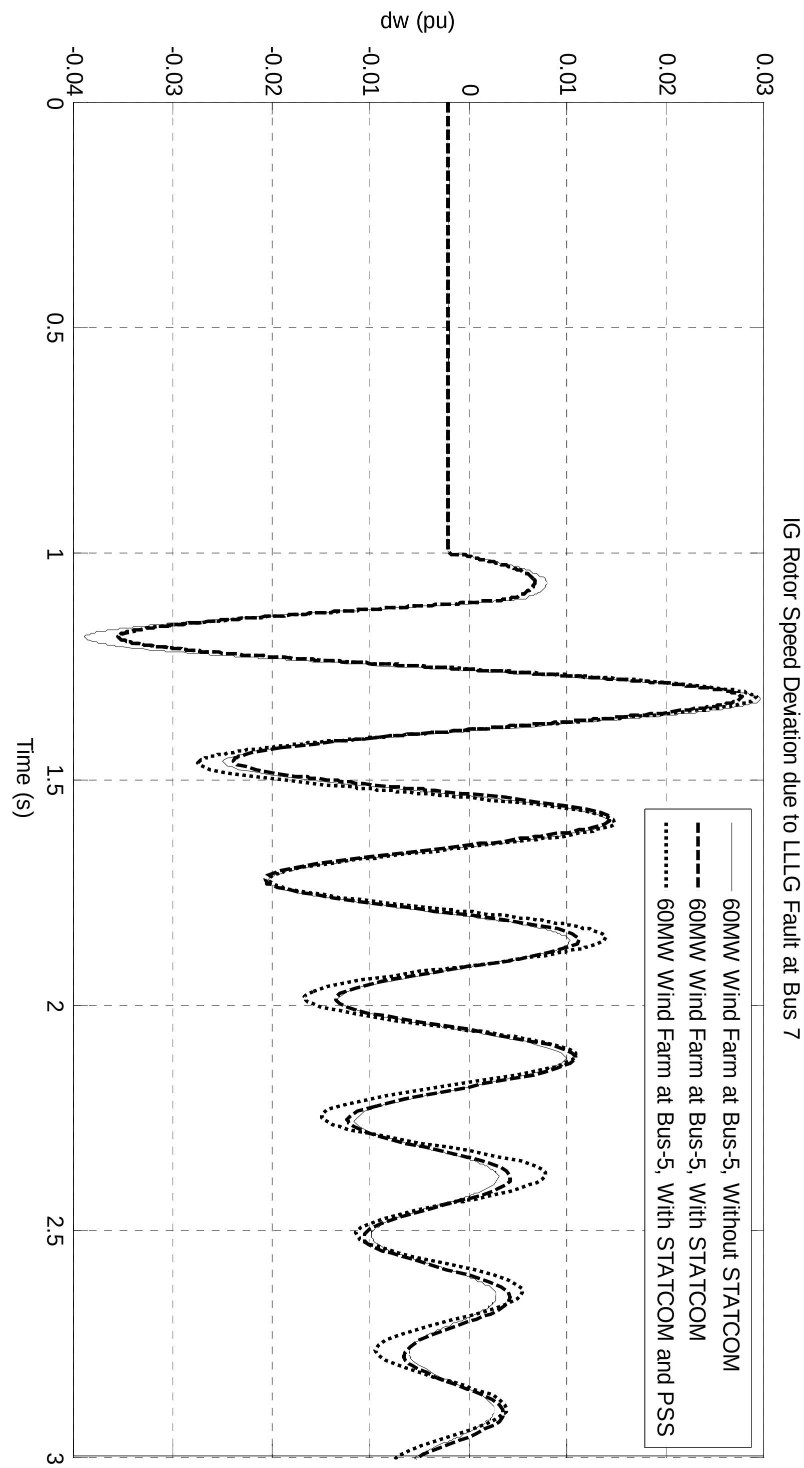

Figure 5.22: IG Rotor Speed Deviation after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 5

Higher ratings of wind farm at the same location within the system is simulated after tuning PSS and STATCOM controllers. The simulations show that the tuned PSS maintained the significant improvement in damping synchronous generators rotor oscillations as can be seen from the following two figures.

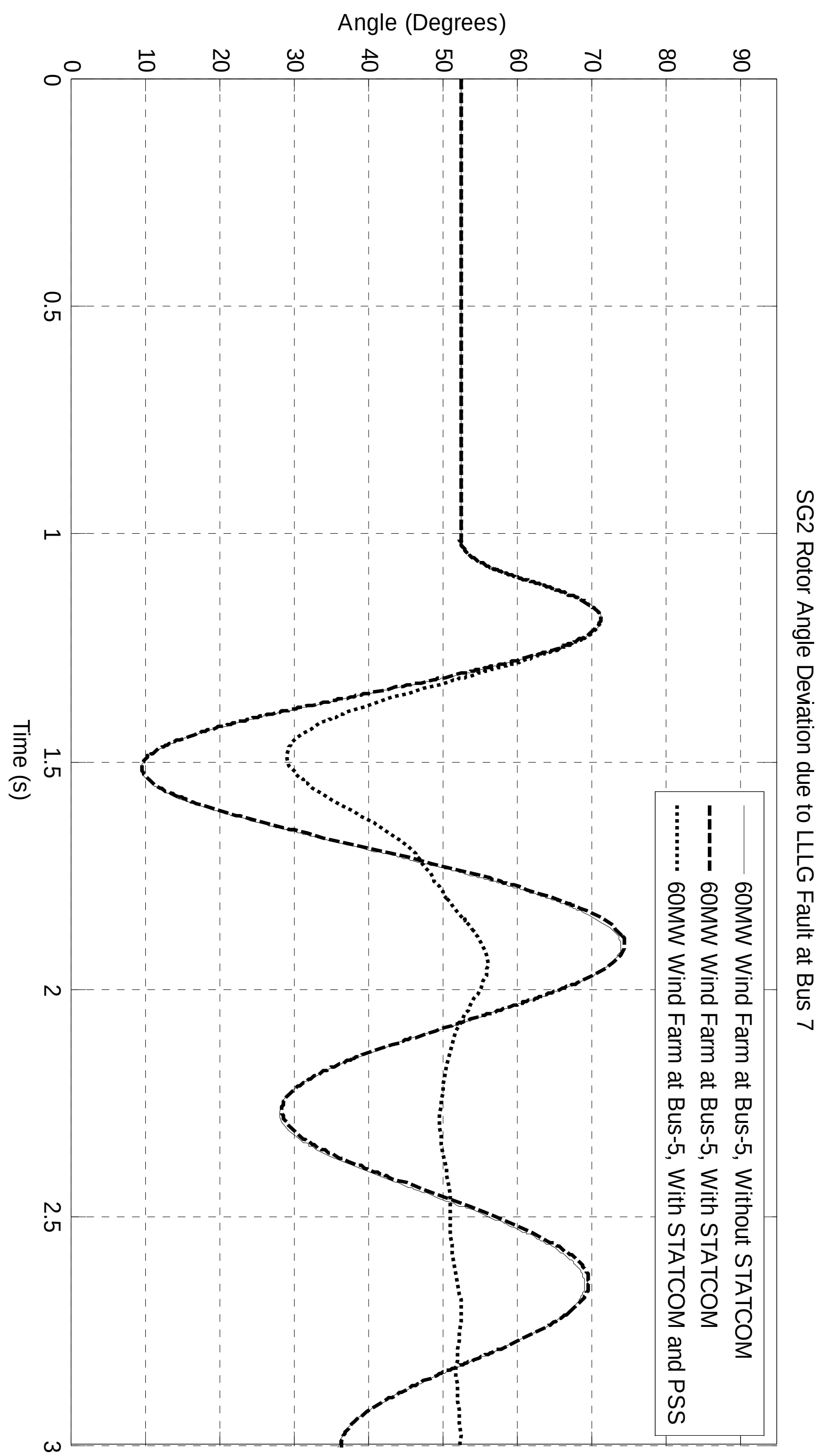

Figure 5.23: SG2 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 5

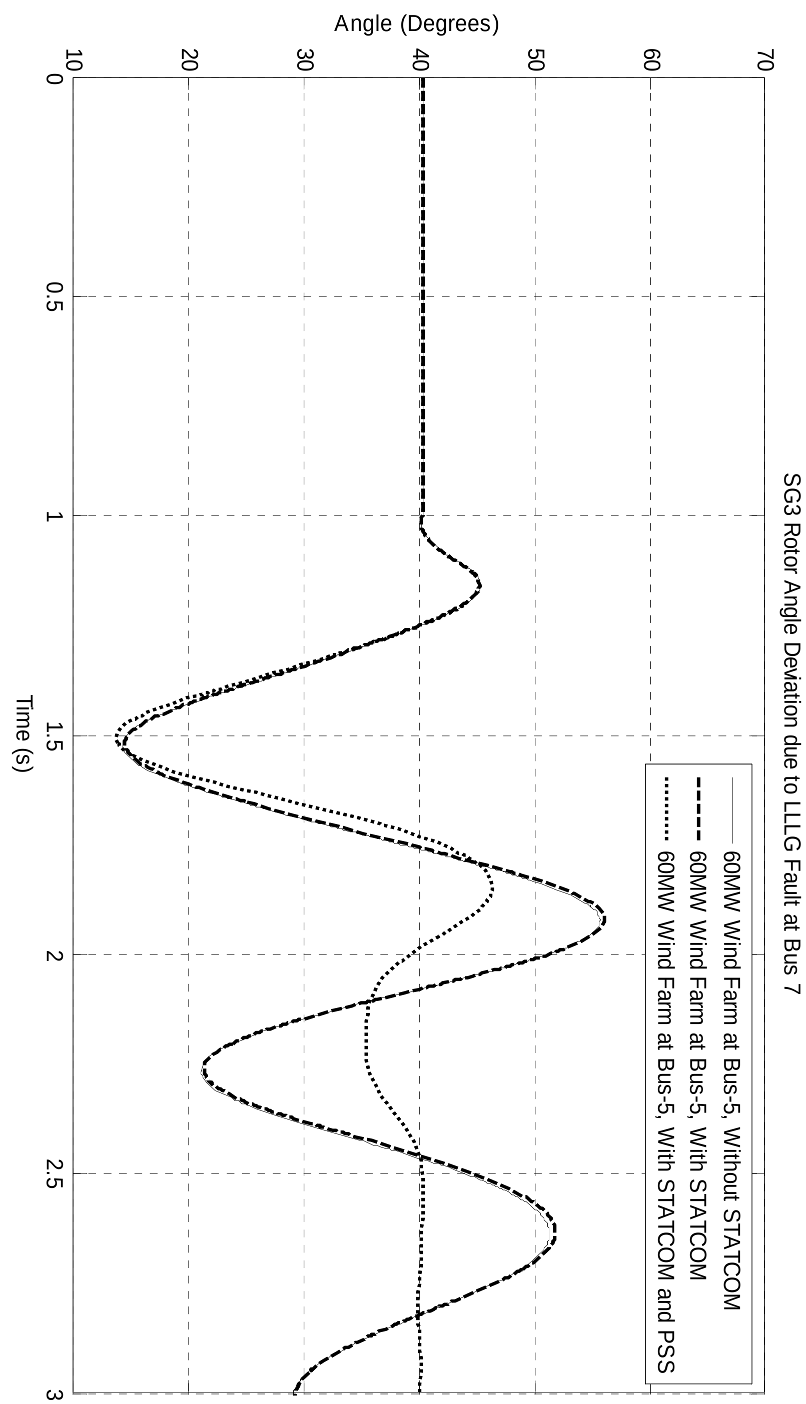

Figure 5.24: SG3 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 5

5.8.3 30 MW Wind Farm at Load Bus 6

System responses when a 30 MW wind farm is now installed at load bus 6 are re-evaluated after tuning both STATCOM and PSS controllers.

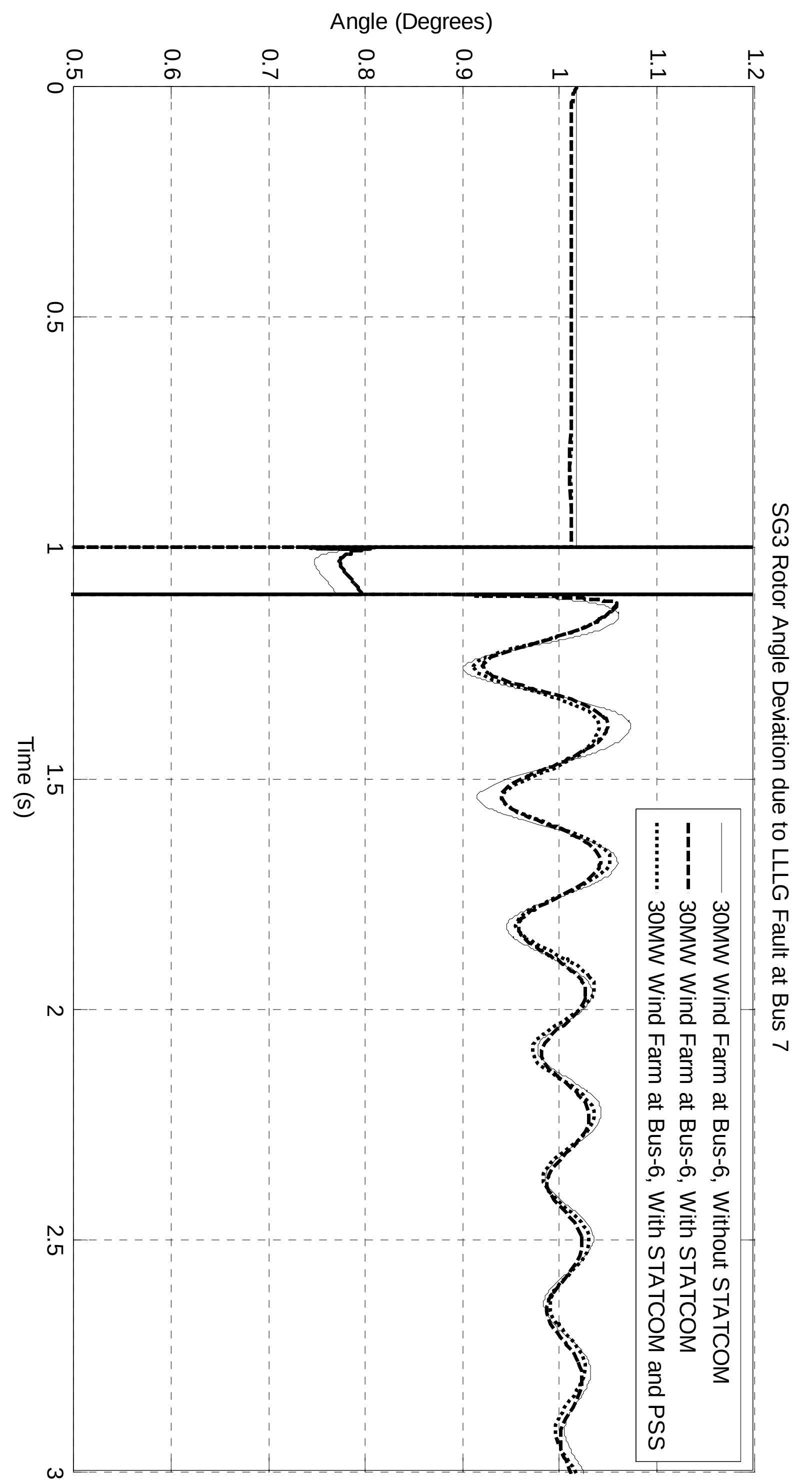

Figure 5.25: IG Terminal Voltage Drop after STATCOM and PSS Parameters Tuning with 30 MW Wind Farm at Load Bus 6

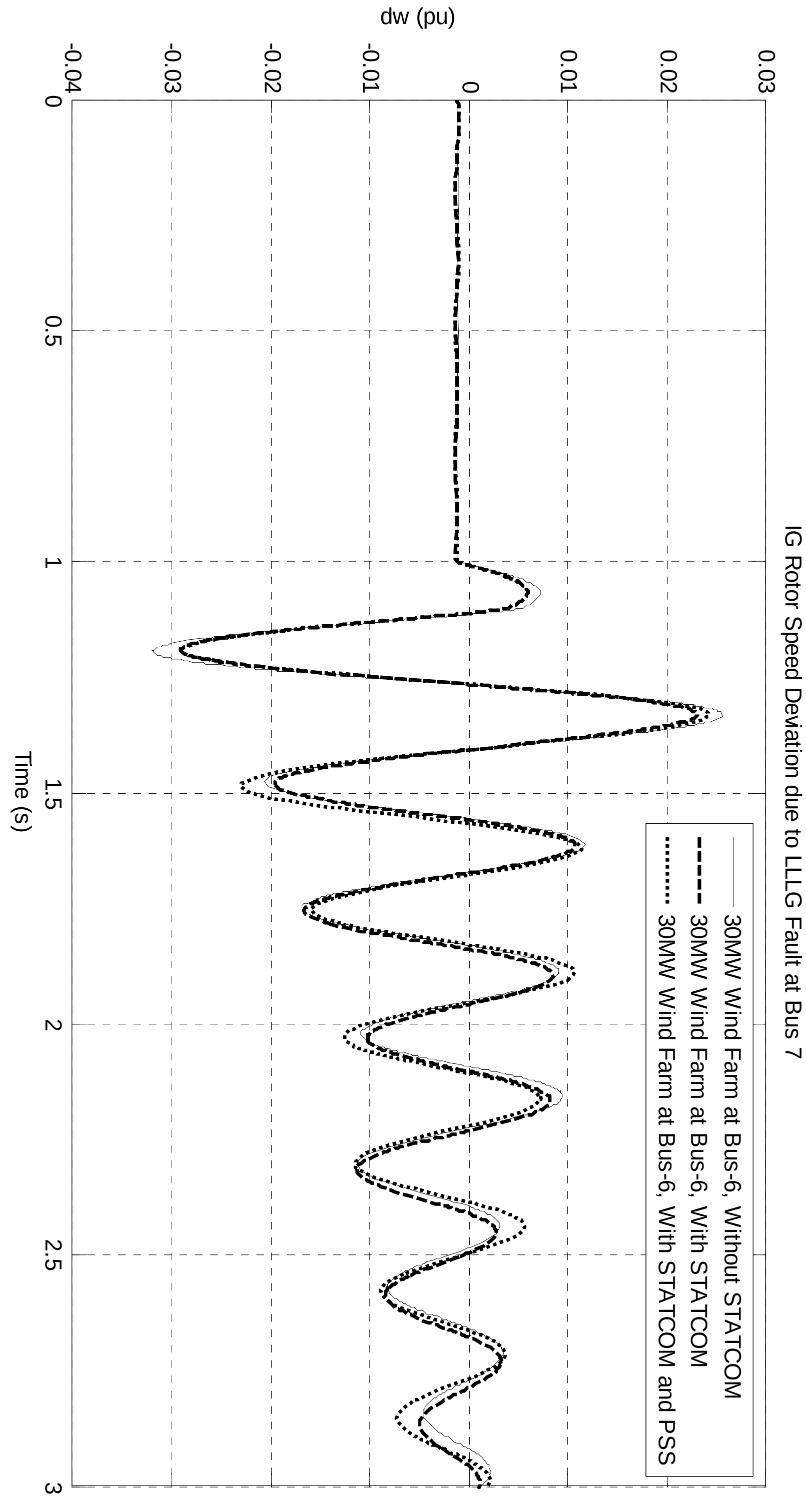

Figure 5.26: IG Rotor Speed Deviation after STATCOM and PSS Parameters Tuning with 30 MW Wind Farm at Load Bus 6

It can be seen from the above two figures that the terminal voltage drop recovery and induction generators rotor speed deviations are still improved even after re-tuning the STATCOM controller and PSS.

The damping of rotor angle deviations for both synchronous generators are much improved as can be seen from the next two figures.

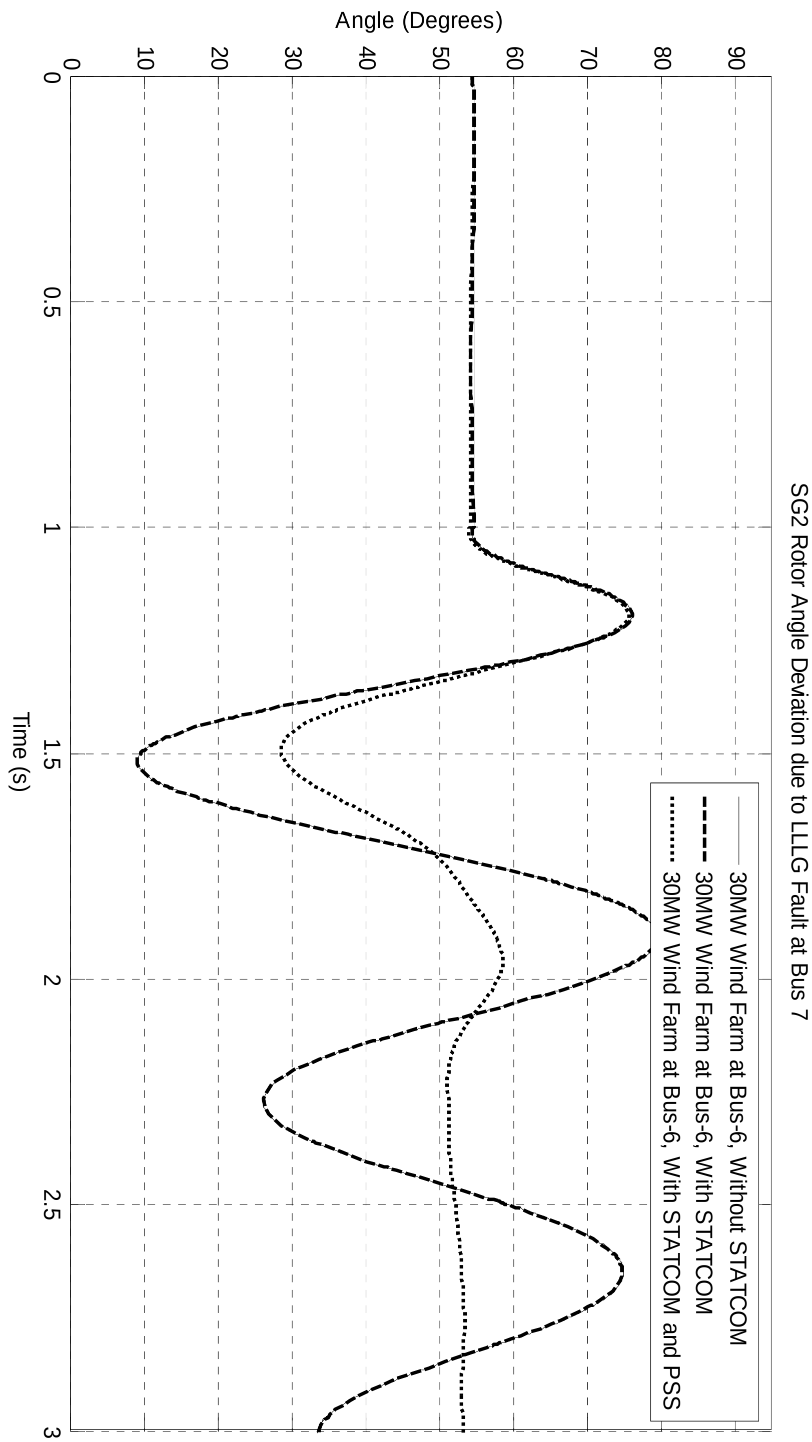

Figure 5.27: SG2 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning with 30 MW Wind Farm at Load Bus 6

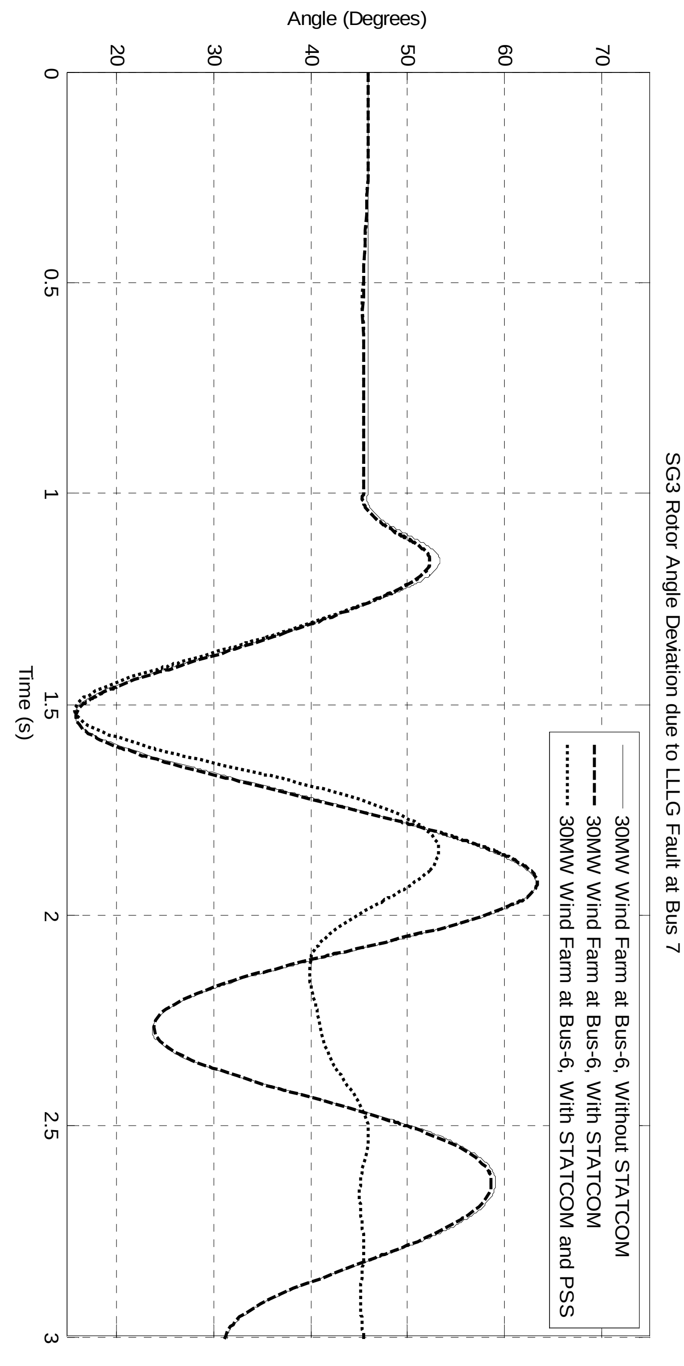

Figure 5.28: SG3 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning with 30 MW Wind Farm at Load Bus 6

5.8.4 60 MW Wind Farm at Load Bus 6

In this case, the re-tuned parameters for the STATCOM controllers and the tuned parameters for the synchronous generators' PSS are used in the time-domain simulations of the nine bus system with 60 MW wind farm located at load bus 6. The responses show a high degree of similarities with the previous three operating scenarios. The recovery of the voltage drop at the terminals of the induction generator as well as its rotor speed deviation are improved.

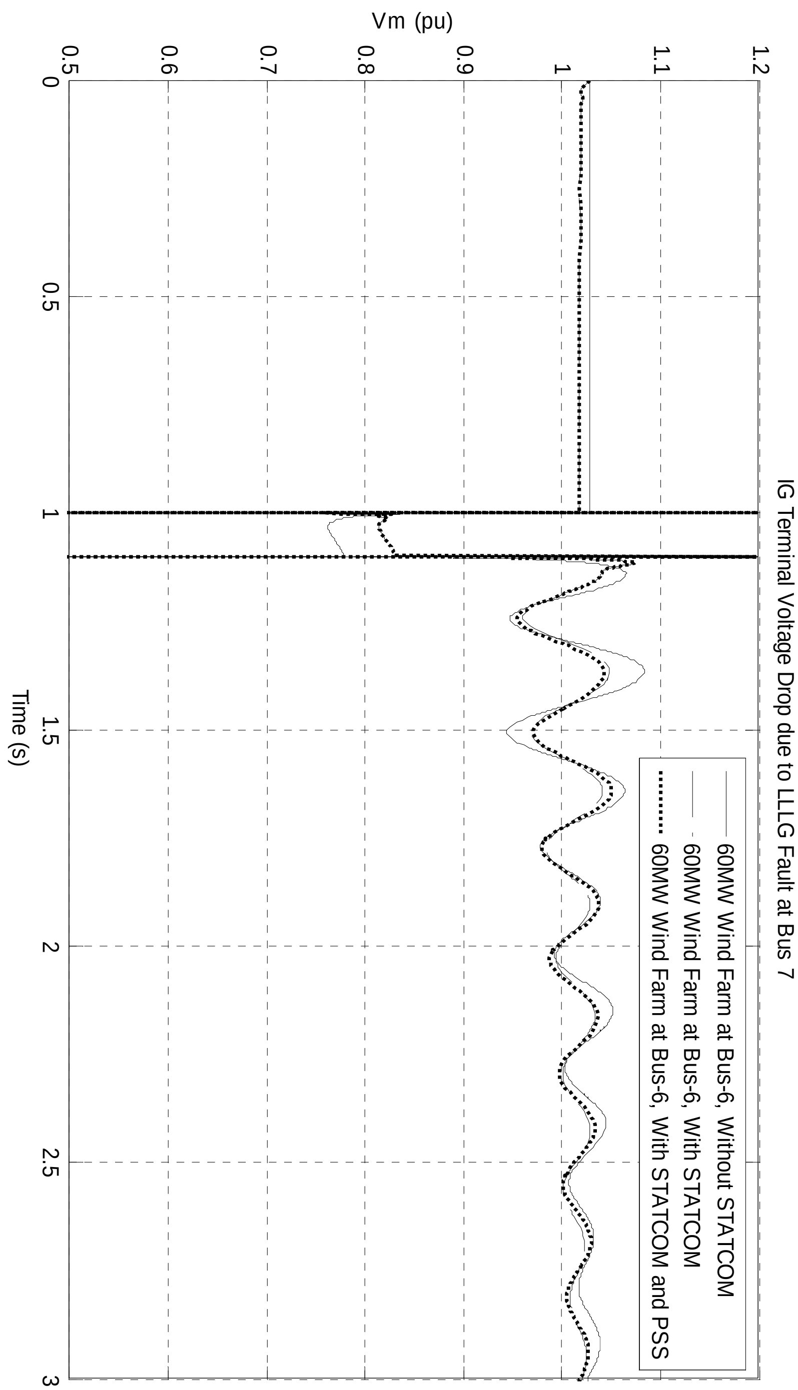

Figure 5.29: IG Terminal Voltage Drop after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 6

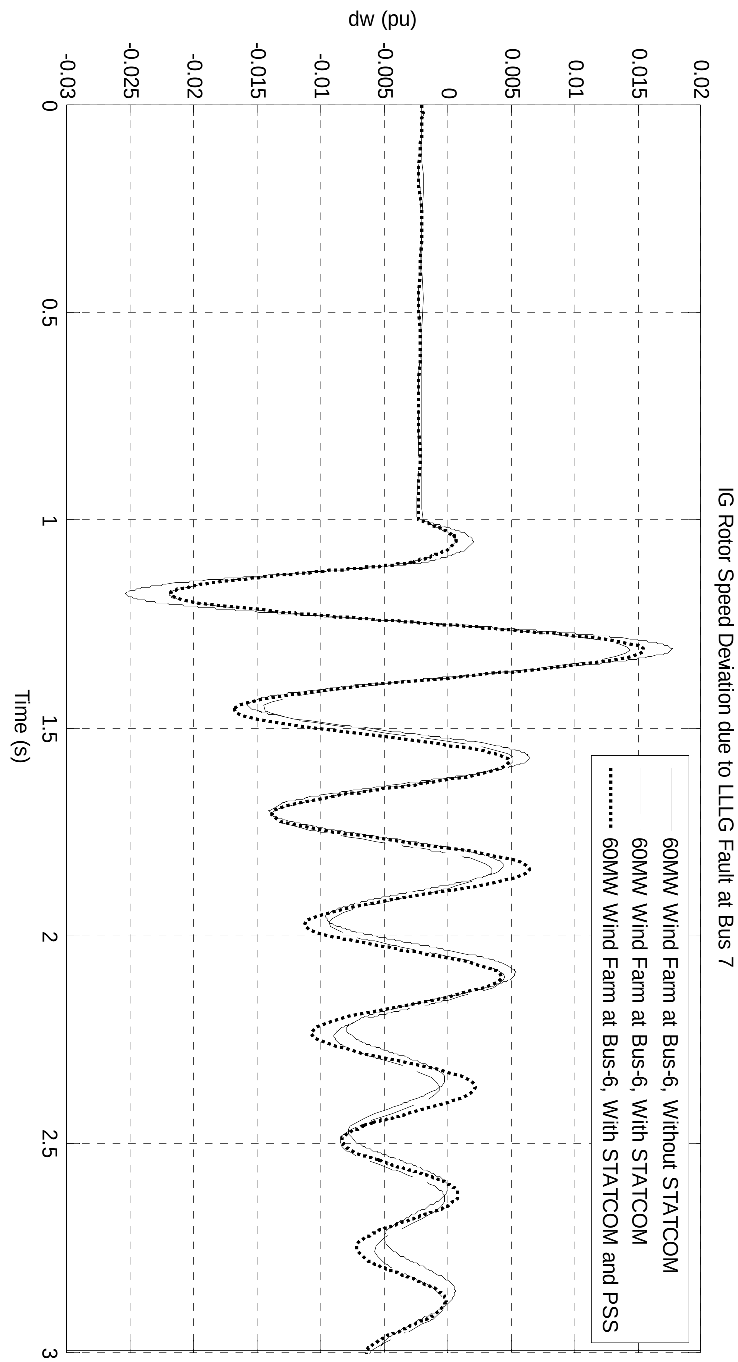

Figure 5.30: IG Rotor Speed Deviation after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 6

Synchronous generators stability is highly improved as well when PSS are included in their excitation system.

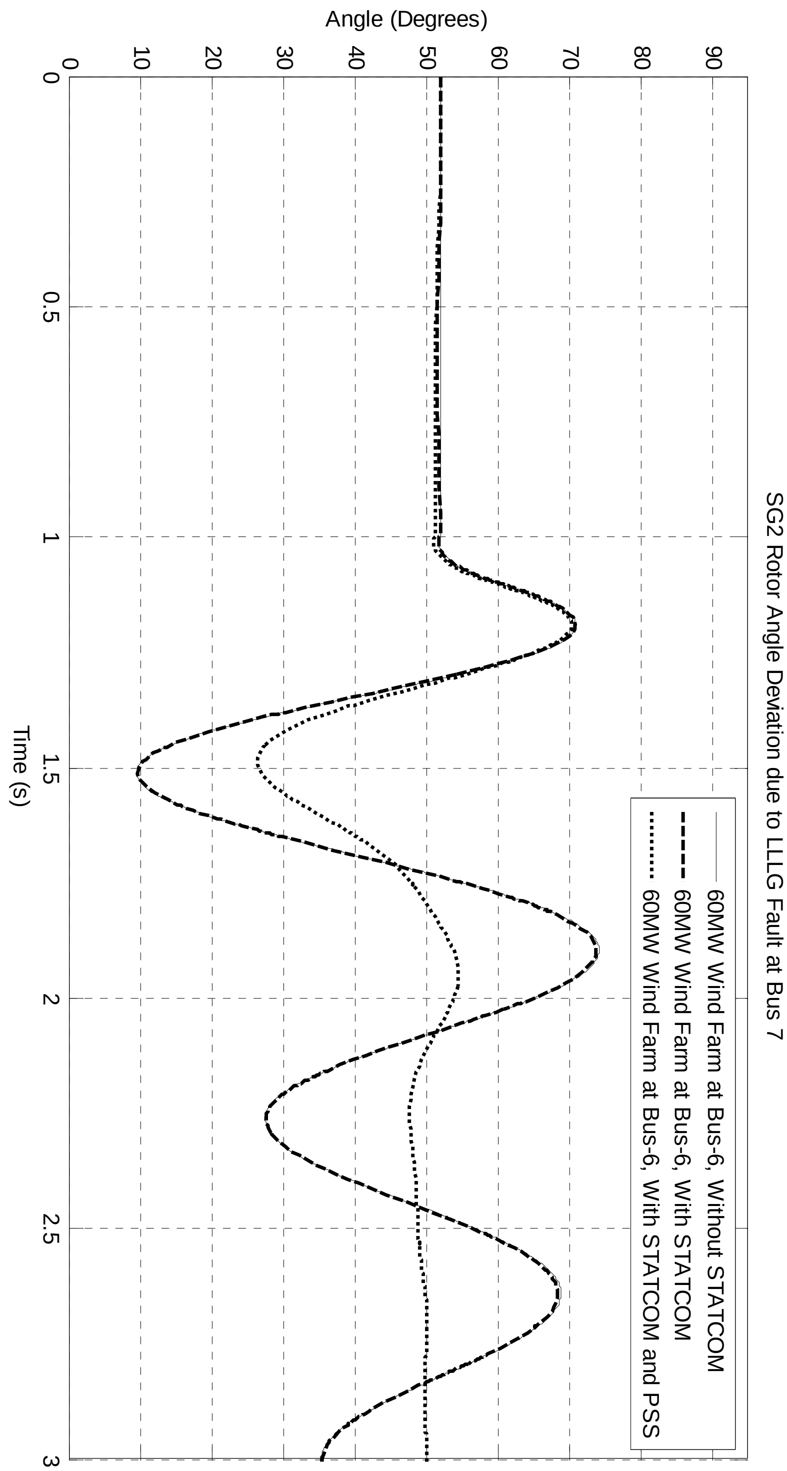

Figure 5.31: SG2 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 6

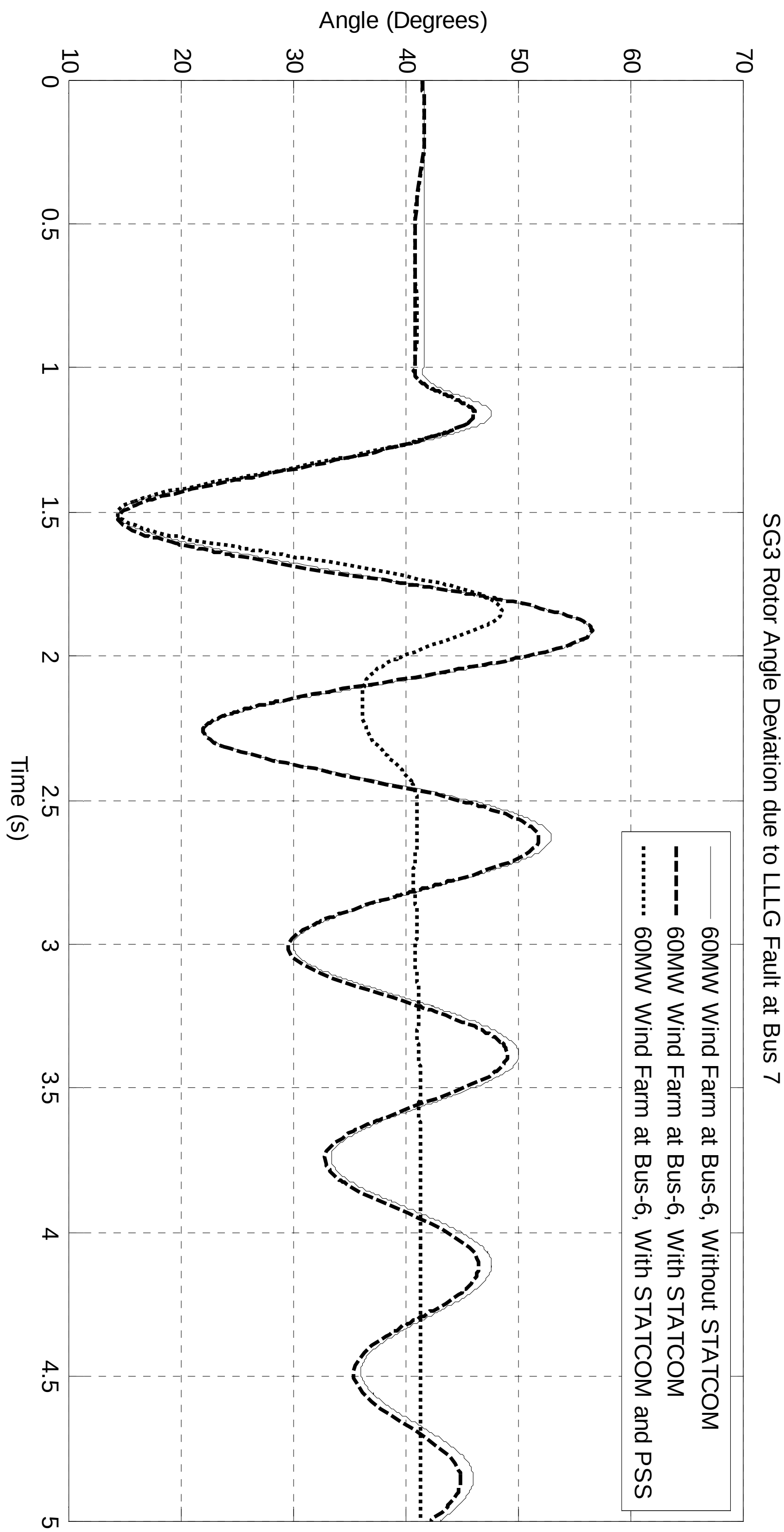

Figure 5.32: SG3 Rotor Angle Deviation after STATCOM and PSS Parameters Tuning with 60 MW Wind Farm at Load Bus 6

5.9 Summary

This section summarizes and compares the results obtained in the previous chapter and this chapter. The comparison will be based on the performance index calculated for each operating scenario as per equation 3.35.

The table shown next illustrates numerically the improvements in the system due to STATCOM controllers' parameters optimization, and STATCOM as well as PSS controllers' parameters optimization. Performance indices for the system in the base case are included for easy comparison.

From the table, it can be concluded that the stability performance of the system is enhanced with optimizing the control parameters of the STATCOM. The enhancement becomes higher with lower wind farm rating, as can be seen for the cases of 30 MW wind farms at load buses 5 and 6. The stability enhancement is estimated to be two times better stability than the base case where no STACOM optimized control is used. With higher wind farm ratings, the stability enhancements still exists but not as much as with lower wind farm ratings.

After adding PSS at the synchronous generators with optimized parameters and optimizing STATCOM controllers' parameters, the stability of the system is further enhanced. This is highly influenced by the improvements that PSS made on damping synchronous generator's oscillations. In this case, stability enhancement is three times better than the base case.

Table 5.3: Performance Indices for the System under Different Operating Scenarios

	PI, System With PSS	**PI, System With STATCOM**	**PI, System Base Case**
Operating Scenario 1: **30MW WF at Bus 5**	0.8879	1.6880	3.1373
Operating Scenario 2: **60MW WF at Bus 5**	1.8453	2.5592	3.1496
Operating Scenario 3: **30MW WF at Bus 6**	1.0615	1.1222	2.4603
Operating Scenario 4: **60MW WF at Bus 6**	1.7155	3.4047	3.5705

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this work, a study is performed to assess the impacts that Distributed Generation has on the stability of electrical power systems. Fixed-Speed Wind Turbines are used in the assessment as one of distributed generation technologies. Dynamic models of different components of the electrical power system and wind technology are presented. Transients of a multi-machine electrical power system are simulated in time-domain.

The following are the outcomes of this work:

- The stability of electrical power systems is related to the penetration levels of WECS. Two cases are studied where WECS penetration corresponds to 10% and 20% of total active power generated by the system, corresponding to 30 and 60 MW of total active power generated by the grid, respectively. It has been shown that system stability performance index degraded with higher WECS penetration.
- The location of WECS within the system and its electrical distance from the fault has an impact on the stability of an electrical power system.

- STATCOM is used as a means for induction machines transient stability enhancement due to its capability in recovering its terminal voltages by injecting or absorbing reactive power from the system. Its AC and DC voltage controllers have been successfully tuned using simple genetic algorithm technique.
- The designed controller is tested for its effectiveness under more than one operation condition. It is proven that STATCOM controllers with the new tuned parameters are improving terminal voltage drops and rotor speed deviation of Wind Farm induction generators.
- An improvement in synchronous generators rotor angle is noticed after tuning STATCOM control parameters.
- Power System Stabilizers are used with the synchronous machines for further stability improvement. Tuning PSS parameters is done using simple genetic algorithm used to tune STATCOM internal controllers. STATCOM controllers are re-tuned after using PSS.
- Power system performance indices calculation and non-linear time-domain simulations are carried out for testing and validating the effectiveness of STATCOM and PSS tuned parameters. It can be concluded that both controllers have contributed to a recordable improvement in electrical power system stability with the presence of WECS.

6.2 Future Work

I recommend the following as a good area to look at while working in the field of electrical power systems stability in presence of WECS:

- STATCOM internal AC and DC voltage controllers are tuned up independently and simultaneously. I propose that while tuning control parameters to take into account coordination between those different control parameters.

- A simple Fixed-Speed Wind Turbine Model is used in this study. The literature is full of more detailed models where the shaft, turbine blades, control schemes, and interface to the grid electronics are described in detail. It is good to re-asses the performance that such models have on the stability of electrical power systems.

- Control input to PSS is chosen to be rotor speed deviation while this input can be changed to any other signal.

- System dynamics are studied under sever faults occurred at high voltage network and outside WECS. It is good to consider in the future studying system dynamics by applying sever faults at low voltage side of the network and within WECS.

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